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EXTREME WIND SPEEDS, GUSTINESS, AND VARIATIONS WITH HEIGHT FOR MIL-STD-210B

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13. ABSTRACT MIL-STD-210A, "Climatic Extremes for Military Equipment," is being revised. The revision will include two sets of windspeed design goals for military equipment being developed for worldwide usage over land: (1) the speed up to which "operations" are expected to proceed, (2) the speed that equipment should "withstand" without irreversible damage. The windiest location in the world for 1 percent or more of the time during the windiest month (the "operational" extreme) is along the north coast of Scotland. Stornoway, Scotland is typical of this general area. Frequency distributions of the wind for Stornoway indicate 1-, 5-, and 10-percent 1-min speeds of 43, 36, and 33 knots respectively (at a height of 10 ft) with associated gusts up to 62 knots for the windiest month, December. The strongest winds in the world, aside from those on mountain peaks and in tornadoes, occur in Pacific typhoons. Naha, Okinawa, is situated in an area of the Pacific noted for its high incidence of typhoons. Wind extremes recorded at Naha are used as basis for developing "withstanding" extremes. For a 10 percent risk and durations of exposure of 2, 5, 10 and 25 years, the expected 1-min wind is 119, 140, 156, and 176 knots, respectively, with associated gusts up to 202 knots. A study of gustiness and variations of wind with height during strong wind regimes is presented. Nomograms of gust factor versus gust duration and steady wind speed are used to assign the most dynamically effective gust according to equipment dimensions. Based on a power-law relationship, factors for adjusting windspeed to a common height to describe windspeed and gusts over the vertical extent of military equipment usage are presented. Also included is a tabulation of wind statistics for selected stations considered in the search for worldwide wind extremes.

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Extreme Wind Speeds, Gustiness, and Variations With Height for MIL-STD 210B

I. INTRODUCTION

MIL-STD-210A "Climatic Extremes for Military Equipment"—a DOD document which is regulatory in nature on the Army, Navy, and Air Force—is being revised to MIL-STD-210B. Amongst other environmental extremes in MIL-STD-210B, there will be two sets of windspeed design goals for military equipment being developed for worldwide usage over land: (1) the windspeed up to which "operations" are expected to proceed; and (2) the speed that equipment should "withstand" without irreversible damage even though the critical speed for operations is exceeded. The withstanding capability can be attained through the basic integrity of the designed equipment or through use of auxiliary "tie-down" kits.

The present MIL-STD-210A provides only one set of values, and these are most applicable to the "withstanding" problem. Guidance furnished by the Special Assistant for Environmental Services (SAES) of the Joint Chiefs of Staff (JCS) indicates that the speed for operations (for example, the landing of an aircraft) will be a value that is exceeded only 1 percent of the time in the windiest month at the windiest geographical area over which military operations are conceivable. JCS (SAES) further suggests that for "withstanding" there should be a family of speeds which have only a 10 percent probability of being attained in geographical

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areas subject to strong winds during an exposure life of 2, 5, 10, or 25 years considered applicable to the spectrum of field lives of military equipment.

2. BACKGROUND

The geographical areas applicable to establishing the "withstanding" speeds are not necessarily windy by usual standards, that is high averages or daily speeds, as in areas for which the standard for "operations" must be determined. For example, 1 percent windspeeds during the windiest month may approach 40 mph in the windy Great Plain States of the U.S.A., an "operational problem"; but long term extremes applicable to "withstanding" (often exceeding the speed defined as a hurricane wind, 75 mph) are more likely on islands and along coasts subjected to tropical and extra-tropical cyclones. Hurricane coasts have much lower average and 1 percent values than windy interior areas at mid- and high-latitudes. However, there are some mid- and high-latitude coastal areas for which both "operational" and "withstanding" extremes are high.

To decide upon speeds commensurate with "operational" and "withstanding" calculated risk design philosophy views of the JCS (SAES), wind records from operational weather stations all over the world must be used excluding the area south of 60°S and isolated locations of anomolous conditions. At most observatories, windspeeds are observed every six hours for internationally established synoptic weather observations. At many locations, mostly airports, observations are recorded every hour. Unfortunately, wind observations and equipment are far from standard. For example, in spite of the great variation of speed with height above the ground in the lower tens and even hundreds of feet, there is no universally accepted standard anemometer height. The international standard height for anemometers, 10 m, is seldom used. Also, the height above the ground is a fictitious value of little use in calculating wind at other heights for anemometers located amongst dense building areas if the effective heights of the surrounding buildings is not properly considered. In the U.S.A., there has recently been a trend to expose anemometers at major weather stations, mostly airports, at aircraft wing levels of 10 to 20 ft, but some of the older exposures were on hangars and towers.

Another problem is the period of time over which the wind is averaged to make it representative of the synoptic weather situation, the basic use of the observation. Panofsky and Brier[1] state "...the spectrum of the wind variance has a great deal of energy near periods of two to three minutes, implying gusts every

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1. Panofsky, H.A. and Brier, G.H. (1958) Some Applications of Statistics to Meteorology, Pennsylvania State University, p. 146-7.

two to three minutes. This means that a one-minute wind average now and a one minute wind average a minute later may come out quite differently. In fact, it appears that winds near the surface should be averaged for at least 30 minutes before really stable estimates can be expected." This knowledge has apparently had little, ifany, influence on the averaging periods used by various observing networks. In past years, counting the number of miles of wind passing the anemometer in 5 min and multiplying by 12 to obtain the miles per hour was the usual U.S. Weather Bureau observation. Very good records of these 5-min synoptic values and daily extremes were kept until shortly after World War II when more sophisticated indicating and recording instruments (which provide continuous records of speed averaged over only a few seconds) came into use (U.S.W.B.[2]). In continuing the attempt to make wind observations meaningful of the synoptic picture, the current standard U.S. observation is an average for 1 min. However, in England and Canada, the climatic data published are hourly averages. Also, a 10-min windspeed is the usual value for synoptic observations when recorders are available, otherwise it is something over 15 sec (Shellard[3]). In 1947 the International Meteorological Organization established a 20-min average for synoptic weather reports, but this rule is not followed (Court[4]).

Gusts are indicated in some climatic summaries when instrumentation has this capability, but are not often recorded. Therefore, studies of wind climatology, such as the speed exceeded 1 percent of the time or the speed with only a 10 percent probability in several years, are best based upon standard observations, often called "steady winds." However, since it is the gust which may be critical to operations or "withstanding" during strong steady winds, it is important to specify the strength of gusts. Careful attention must be given to the time over which gusts are averaged, the speed of the steady wind, and the effect of height above ground. The sizes (or durations) of gusts most pertinent to the spectrum of equipment sizes must be related to this observational data. The MIL-STD-210A of 1953—based only on then available 5-min steady winds—specifies an "instantaneous" gust of 150 percent of the steady (5-min) speed at all heights. This peak speed is said to have a gust factor of 1.5.

In recent years design of large structures such as television transmitter towers, "skyscrapers," missiles (on the pad), and bridges has reached the point of sophistication where fatigue of the structure due to vortex shedding, which is

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2. U.S. Weather Bureau (U.S.W.B.) (1963) History of Weather Bureau Wind Measurements, U.S. Dept. of Commerce, Washington, D.C.

3. Shellard, H.C. (1968) Tables of Surface Wind Speed and Direction Over the United Kingdom, Meteorol. Off. 792, Her Majesty's Stationary Office, London.

4. Court, A. (1953) Wind extremes as design factors, J. Franklin Inst. 256(No. 1):39-55.

in resonance with the natural elastic frequency of the structure, must be considered. Davenport[5] has also suggested the application of the power spectrum of turbulence in the wind to this fatigue problem. These treatments are pertinent to such massive and elaborate structures, but would probably be of limited utility in design of standardized transportable military equipment, the goals of this study. Also, since the techniques for application are not well established, no attempt to handle this so-called elastic response problem is included herein.

Some studies of strong wind extremes for structural design are based on the climatology of the fastest mile (Thom[6] and Breckke[7]). Utilization of such data involves comparing speeds averaged over a spectrum of time periods, a very unsatisfactory approach if shorter period gusts are to be derived since gust factors apply to a specific averaging period. Also, since speed of the wind is dependent upon the time period over which it is averaged, the speeds in such studies are not truly comparable.

Durst[8] notes that the use of lighter construction material has necessitated a more detailed knowledge of short duration winds, and has provided some preliminary models showing how speed increases as averaging time decreases. Mitsuta[9] states that structural failure studies have indicated that "very short duration wind forces might be effective for destruction of buildings or other constructions". One such situation caused the collapse of cooling towers in England and was presented in detail by Shellard.[10]

Studies of the relationship of gusts to the steady wind and their variation with speed, height, thermal stratification, and terrain have culminated in general

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5. Davenport, [illegible] Dependence of Wind Loads on Meteorological Parameters, Paper [illegible] on Buildings and Structures, Vol. I, University of Toronto Press, [illegible]

6. Thom, H.C. [illegible] Frequency of maximum wind speeds, Proc. Am. Soc. Civil Eng. 80(No. 539).

7. Breckke, G.N. (1959) Wind Pressures in Various Areas of the United States, Building Material and Structures, RPT152, NBS, U.S. Dept. of Commerce.

8. Durst, C.S. (1960) Wind speeds over short periods of time, Meteorol. Magazine 89(No. 1056):181-186.

9. Mitsuta, Y. (1962) Gust factor and analysis time of gust, J. Meteorol. Soc. (Japan) 40(No. 4):242-244.

10. Shellard, H.C. (1967) Collapse of cooling towers in a gale, Ferrybridge, November 1965, Weather 22:232-240.

agreement concerning the nature of these relationships (Davis and Newstein,[11] Camp,[12] Shellard,[13] Mitsuta,[9] Durst,[8] Deacon,[14] Sherlock,[15, 16] Fichtl et al.[7] Brook and Spillane,[18] and others). However, quantitative results have varied depending on the data and analytical methods used.

This paper provides the climatological background for specifying gusts of various durations during strong winds at several climatically different locations from operational weather station recorder charts. The intent is to provide the user with gust factors truly representative during operational and catastrophic "withstanding" speeds which may be used to determine maximum windspeeds relevant to various sizes of equipment, information on the variation of windspeed with height, and finally, climatological background for specifying the extreme wind design criteria recommended for MIL-STD-210B.

3. GUST FACTOR RELATIONSHIPS

As indicated in the background, usually available wind observations—from which climatologies are available—are speeds averaged over a minute or more. Gusts during such averaging periods can often build sufficient force to exceed the threshold value required to prevent operations or to do irreversible damage.

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11. Davis, F.K. and Newstein, H. (1968) The variation of gust factors with mean wind speed and with height, J. Appl. Meteorol. 7(No. 3):372-378.

12. Camp, D.W. (1968) Low Level Gust Amplitude and Duration Study, NASA TM X-53771, George C. Marshall Space Flight Center, Huntsville, Alabama.

13. Shellard, H.C. (1965) The estimation of design wind speeds, Wind Effects on Buildings and Structures, National Physics Laboratory Symposium (No. 16):p 30-51.

14. Deacon, E.L. (1955) Gust variation with height up to 150 meters, Quart. J. Roy. Meteorol. Soc. (London) 81:563.

15. Sherlock, R.H. (1947) Gust Factors for the Design of Buildings, Int. Assoc. for Bridge and Structural Engineering, Vol. 8, p. 207-235.

16. Sherlock, R.H. (1952) Variation of wind velocity and gusts with height, Paper No. 2553, Proc. Am. Soc. Civil Eng., p 463-508.

17. Fichtl, G.H., Kaufman, J.W., and Vaughan, W.W. (1969) Character of atmospheric turbulence related to wind loads on tall structures, J. Spacecraft 6(No. 12):1398-1403.

18. Brook, R.R. and Spillane, K.T. (1970) The variation of maximum wind gust with height, J. Appl. Meteorol. 9(No. 1):72-78.

The relationship of such gustiness to the standard observations must be known in order to provide "operational" and "withstanding" extremes for MIL-STD-210B.

Sherlock[15] indicates that a gust must have a duration such that its size is about 8 times the downwind dimension of a structure in order to build a force on the structure commensurate with the gust speed. As an example, for a structure with a 12.5-ft downwind dimension a gust must be 100-ft long to build up full dynamic pressure. For a speed of 100 fps (59 knots), a gust need act for only 1 sec to build up to full force on such a structure. Larger structures require a longer duration gust. A gust of several seconds is often considered as typical of the critical duration in buildings of up to 100 ft for typical extreme speeds, say 100 knots. For stronger winds, the required duration will be even shorter. Table 1 indicates the gust duration required to build up full dynamic pressure on structures up to 100 ft.

Table 1. Duration (sec) of Gusts Required to Allow Full Buildup of Force on Structures

Speed		Down-wind Dimension				
Knots	(fps)	5 ft	10 ft	25 ft	50 ft	100 ft
		Gust Duration (sec)				
25	42	0.9	1.9	5	9	10
50	84	0.5	0.9	2	5	9
75	127	0.3	0.6	1.6	3	6
100	169	0.2	0.5	1.2	2	5
125	211	0.2	0.4	0.9	1.9	4
150	253	0.2	0.3	0.8	1.6	3

Another aspect of the gust-size problem is the physical response of structures to gusts of various duration. Large structures such as buildings have great mass, and it can be contended that there is insufficient time for reaction to short period gusts. Therefore, only the force of the steady wind speed would be important in their design. Newberry et al[19] reported on wind loads experienced on an instrumented 18-story rectangular office building, 142 ft by 58 ft. He finds that displacement of this building would be about 1.5 ft during the course of a 3-sec gust speed of 65 knots if the building were free floating. He states: "Such displacement would be quite unacceptable and the conclusion must be drawn that the

19. Newberry, C.W., Eaton, K.J., and Mayne, J.R. (1968) The nature of gust loading on tall buildings, Wind Effects on Buildings and Structures, University of Toronto Press, Proc. of the International Research Seminar held at the National Research Council of Canada, Ottawa, Canada, 11-15 September 1967.

inertia of the building plays only a small part in resisting the effect of gust loading, at least down to the 3-sec averaging period". He further states: "In respect of cladding the indications are that even shorter gusts are significant, but for the present their limits have not been explored."

On the other hand, Newberry et al[19] presents data which support the need for a gust to have a duration such that it is about 8 times the downwind dimension of the structure in order to build up full force. His measurements in a wind of about 40 knots show that the gust factor relative to the 1-min speed derived from the force on the building are about those for 5- to 10-sec gusts, supporting the values in Table 1.

Most studies of gustiness are from micrometeorological research. Though measurements obtained from such experiments are generally superior to operational data because of refined anemometry, such studies hardly ever provide data for the very strong windspeeds important in design of military equipment. Therefore, an attempt was made herein to analyze gust data for a more meaningful spectrum of windspeeds. Also included are some other pertinent data from unusually strong winds and relevant research findings.

3.1 Data

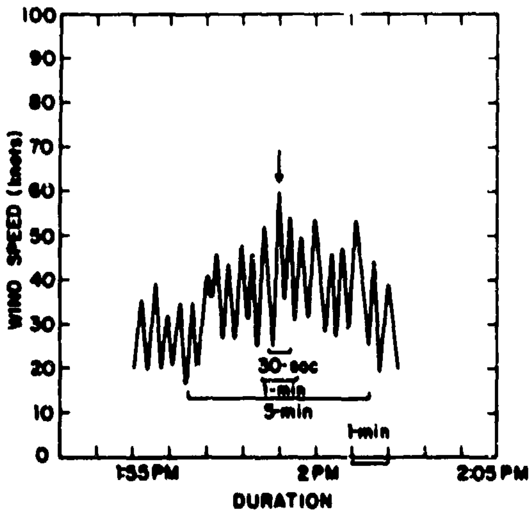
Original wind gust recorder charts containing strong, steady speeds, available in the inventory of the National Weather Records Center, were requested from the Environmental Technical Application Center (ETAC). Stations, dates and anemometer heights of the data provided, which were used in our analysis, are listed in Table 2. An evaluation of the response times of wind measuring instrumentation from which the data were taken is presented in Appendix A.

In order to have sufficiently stable samples of data to examine variations of gustiness with speed, 10-knot windspeed class intervals were chosen (for example, 20-29 knots, 30-39 knots, etc.). One method of obtaining gust factors from the data was to mark off equal time intervals on the gust recorder chart, take the steady windspeed and compute factors for the highest gusts occurring within the interval. Another possibility was to use a long time interval, say an hour, and compute the gust factors from the highest 5-min, 1-min, or 30-sec winds, no matter where they are located in the hour interval. Assuming that the most likely gust configuration is symmetrical, as shown by Camp,[12] it was decided that the gust being measured should be in the center of the averaging period. This concept is presented graphically in Figure 1. Since the "Manual of Surface Observations" (Circular N) used by the National Weather Service, Air Force, and Navy prescribes the recording of the average 1-min

Table 2. Stations, Dates, Number of Observations and Anemometer Heights of Primary Data

Station	Anemometer Height (ft)	No. Obs	Date
Adak, Alaska NS	80	7	February, 1952
	75	81	March, 1954
	75	14	September, 1956
	75	60	March, 1958
	75	47	November, 1958
	75	4	October, 1958
	75	21	May, 1959
	58	10	November, 1961
	25	38	November, 1964
Argentia, Nfld, FWC	56	30	September, 1955
Azores/Lajes Field	10	16	February 1960
Cherry Point, N.C. MCAS	95	13	September, 1955
Falmouth, Mass/Otis AFB	13	11	September, 1960
Guam/Agana NAS	43	1	November, 1957
	14	41	April, 1963
Guam/Anderson AFB	13	4	November, 1962
New Orleans, La. WBAS	20	18	September, 1965
Okinawa/Futema MCAF	28	9	October, 1961
Okinawa/Kadena AB	13	69	October, 1961
Patuxent River, Md/NAS	85	10	October, 1954
Quonset Point, R.I./NAS	84	3	September, 1954
Rapid City, S.D./Ellsworth AFB	13	30	February, 1963
Thule, Greenland/AB OP Site	13	11	March, 1960
		Total 548	

Figure 1. Method Used to Determine Windspeeds of Differing Durations. The peak gust within 2.5 min of the hour is indicated by an arrow. For this example, the 5-min speed is 38 knots, the 1-min speed is 40 knots, the 30-sec speed is 43 knots, and the 2-sec peak is 60 knots



speed, this speed was used to describe all relationships. Ratios of the 5-min and 30-sec averages and peak gust (about 2 sec as will be noted in the next section) to the 1-min wind were computed. For example, the gust described in Figure 1 has a 1-min average speed of 40 knots, a 5-min average speed of 38 knots, a 30-sec average speed of 43 knots, and a peak gust of 60 knots. The 5-min factor is 38/40 or 0.950, the 30-sec gust factor is 43/40 or 1.08, and the peak gust factor is 60/40 or 1.50. Since the 1-min speed is 40 knots, these factors would be assigned the 40-49 knot class interval in subsequent statistical summaries. A total of 548 such observations were studied. The method used was to make observations centered on the highest peak (2-sec) gust within 2.5 min of the hour. However, on occasions when a higher gust fell within 2.5 min of the gust chosen, that gust then became the center of the observation. The vertical arrow in the center of Figure 1 points to the 2-sec gust chosen at 2:00 P.M. Because of the scarcity of recorded steady winds over 60 knots, gusts were studied at 15-min intervals when such winds were encountered.

Wind near the earth's surface is very sensitive to the terrain; consequently, any particular location is likely to have its own gust characteristics. Since data for this section were provided from the many locations listed in Table 3, pooling the observations should effectively limit the influence of any one location. The anemometer heights range from 10 to 95 ft. The average height of these is roughly 50 ft.

3.2 Gust Factor Statistics

Means and the range of ratios of 5-min, 30-sec, and 2-sec averages to the standard 1-min speed for the sample of 548 observations taken from the

operational recorder charts studied are shown in Table 3. The 50-, 75-, 90-, and 98-percentile values and the standard deviations of 2-sec gust factors are shown in Table 4.

Observations at anemometer heights above and below 50 ft were separated with resulting mean heights being approximately 75 and 15 ft. The number of observations in each windspeed category for these two height classes and the average heights are shown in Table 5. The mean, standard deviation, and the 50, 75, 90, and 98-percentile values of the 2-sec gust factors at 15 and 75 ft are shown in Table 6. A study of Tables 3, 4, and 6 reveals:

(1) As shown in Table 3, the expected decrease in the mean 2-sec gust factor with increasing 1-min speeds is evident except at the 70-79 knot interval where the sample size is very small. However, when the gust factors at the mean heights of 15 and 75 ft are examined (Table 6), the decrease is much greater at 75 ft; in fact, the gust factor at 15 ft increases slightly for speeds through the 40-49 knot intervals. The standard deviations of the 2-sec gust factors also decrease with increasing speed at 75 ft but behave erratically at 15 ft.

(2) The 2-sec gust factors at 75 ft are less than those at 15 ft at speeds greater than 39 knots, reflecting the decreasing effect of surface friction (on 1-min averages) with height, even as low as 75 ft.

(3) The 30-sec ratios remain nearly constant with increasing speed (Table 3), whereas the 5-min ratios show no obvious trend. Evidently, measurements averaged for at least 30 sec tend to filter out most of the small scale turbulence.

Much of the older extreme wind studies for structural design criteria used well-defined 5-min average speeds (Court[4]). For comparative purposes, ratios of maximum 1-min, 30-sec, and 2-sec averages within each 5-min observation were computed. Median and mean ratios are shown in Table 7. Means and medians are sufficiently close to indicate that the distributions are near normal. The 2-sec gust factors show the same trends as in Table 6, decreasing with increasing speed more rapidly at 75 ft than at 15 ft. Clear trends for the 30-sec and 1-min ratios are evidently clouded by the diverse nature of the data.

The tendency for gust factors to decrease with increasing speed at the nominal height of operational anemometers, 50 ft, is illustrated in Figure 2. The operational anemometer gust factor curves were drawn for a 5-min steady wind. The values were obtained by averaging the mean gust factors for the 15- and 75-ft columns in Table 7; however, the speed categories are in terms of the 1-min speed. Also shown are the findings of Sherlock[15], Durst[8], and Mackey[20] for Typhoon Mary.

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20. Mackey, S. (1965) Discussion of Wind Effects on Buildings and Structures, Her Majesty's Stationary Office, London, p. 422, 423.

Table 3. Ratios of 5-min, 30-sec, and 2-sec Speeds to the 1-min Speed for All Observations Regardless of Anemometer Height

1-min Speed (knots)	No. Obs.	5-min		30-sec		*2-sec	
		Mean	Range	Mean	Range	Mean	Range
20-29	133	0.909	0.692-1.00	1.04	1.00-1.17	1.35	1.07-2.14
30-39	142	0.911	0.771-1.00	1.04	1.00-1.17	1.31	1.06-1.81
40-49	113	0.920	0.732-1.00	1.04	1.00-1.17	1.28	1.04-0.81
50-59	83	0.917	0.778-1.00	1.04	1.00-1.16	1.27	1.08-1.61
60-69	67	0.932	0.783-1.00	1.04	1.00-1.15	1.25	1.03-1.58
70-79	10	0.911	0.855-0.958	1.06	1.03-1.18	1.29	1.06-1.54

*Values in these columns are usually called "gust factors."

Table 4. Distribution of 2-sec Gust Factors Versus 1-min Average Speed for All Observations Regardless of Anemometer Height

1-min Speed (knots)	Standard Deviation	Percentile Values			
		50	75	90	98
20-29	0.172	1.31	1.41	1.58	1.82
30-39	0.149	1.28	1.39	1.50	1.71
40-49	0.146	1.26	1.37	1.44	1.68
50-59	0.114	1.27	1.35	1.41	1.54
60-69	0.140	1.23	1.36	1.44	1.56
70-79	insufficient data				

Table 5. Distribution of Anemometer Heights Versus 1-min Average Speed for the Recorder Charts Studied

1-min Speed (knots)	Less Than 50 ft		More Than 50 ft		Mean Height of All Obs (ft)
	No. Obs.	Mean Height (ft)	No. Obs.	Mean Height (ft)	
20-29	77	17	56	75	40
30-39	66	16	76	73	46
40-49	36	15	77	71	53
50-59	26	15	57	75	57
60-69	41	14	26	78	39
70-79	2	13	8	78	65

Table 6. Distribution of the 2-sec Gust Factors During 1-min Speeds by Approximate Anemometer Height

1-min Speed (knots)	Mean		Std Dev		Percentile							
					50		75		90		98	
	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft
20-29	1.33	1.37	0.122	0.220	1.31	1.30	1.39	1.50	1.45	1.66	1.66	2.07
30-39	1.35	1.27	0.120	0.162	1.32	1.23	1.43	1.33	1.49	1.50	1.71	1.74
40-49	1.36	1.25	0.132	0.138	1.35	1.19	1.40	1.33	1.52	1.42	1.80	1.63
50-59	1.33	1.25	0.105	0.110	1.31	1.25	1.38	1.33	1.44	1.40	1.64	1.51
60-69	1.27	1.21	0.168	0.063	1.31	1.20	1.41	1.24	1.48	1.29	1.57	1.36
70-79	1.37	1.27	Only 2 observations at 15 ft. and 8 observations at 75 ft.									

Table 7. Ratios of 1-min, 30-sec and 2-sec Speeds to 5-min Speeds

1-min Speed (knots)	50 Percentile						Mean					
	1-min		30-sec		2-sec		1-min		30-sec		2-sec	
	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft	15 ft	75 ft
20-29	1.08	1.11	1.12	1.16	1.41	1.44	1.08	1.13	1.12	1.18	1.44	1.55
30-39	1.10	1.10	1.14	1.14	1.45	1.35	1.10	1.10	1.14	1.14	1.48	1.40
40-49	1.08	1.08	1.12	1.12	1.46	1.29	1.08	1.09	1.12	1.14	1.47	1.36
50-59	1.06	1.09	1.11	1.13	1.39	1.36	1.07	1.10	1.12	1.14	1.43	1.37
60-69	1.05	1.10	1.09	1.14	1.38	1.32	1.05	1.11	1.09	1.15	1.34	1.34

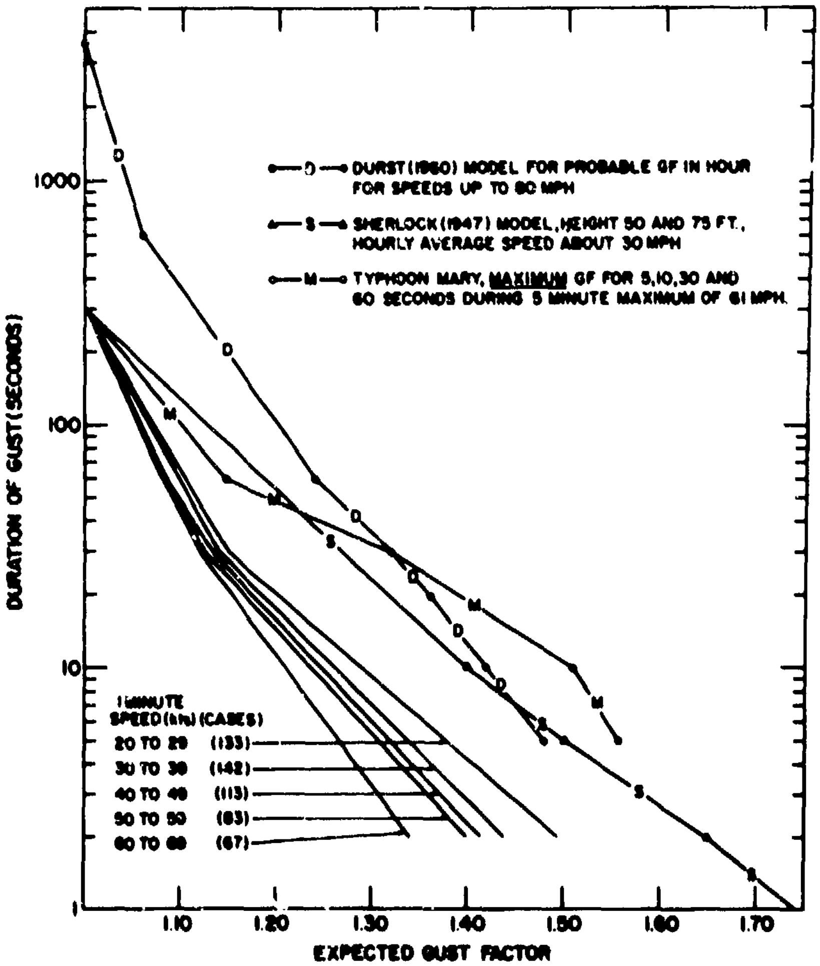

Figure 2. Expected Gust Factor (GF) From Operational Wind Recorders

Sherlock used a special data sample obtained from anemometry equipment designed to indicate gust durations down to 0.5 sec. The gust factors are higher than for the operational anemometers, but Sherlock's data sample was quite limited; his 2-sec value of 1.65 is within the distribution of the operational anemometer data. Durst's[8] statistical model was based upon several samples of 10-min long, high speed recorder, anemometer runs. He obtained the ratio of these sampling periods to their hourly averages in order to obtain the ratios of shorter period values to the hourly values. His empirical data were taken at an anemometer height of 50 ft and limited to speeds less than 42 mph (36 knots). He applied his model to 10-mph (9-knot) class intervals of speed up to 80 mph (70 knots) to obtain expected maximum gusts of various durations. Probable gust factors for 600-, 60-, 30-, 20-, 10-, and 5-sec duration, indicated in Table 8, are nearly the same regardless of the speed. Mackey,[20] in a report on Typhoon Mary when it crossed Hong Kong, derived maximum speeds for 5-, 10-, 30-, and 60-sec duration during the maximum 5-min speed of 61 mph (55 knots). Short duration gust factors are much higher than those in other sources, as can be seen in Figure 2.

In order to determine if there is a difference between gusts occurring from tropical storms and those from extra-tropical storms, samples of data taken from stations with anemometer heights of 10 to 25 ft were selected from the 548 strip charts from operational weather recorders for tropical and extra-tropical storms. Gust factors for 1-min speeds of 20 to 59 knots were combined to increase the stability of the sample. These are compared in Table 9. The 2-sec gust factors appear to be slightly greater for tropical storms, but the significance of this difference needs substantiation. Smith and Singer[21] studied the gust factors for 1-min winds during 1954 when two hurricanes, Carol and Edna, were passing close to Brookhaven National Laboratories, Long Island, New York. Friez Aerovane equipment was located on several levels and the authors determined the gust (assumed to be 2-sec duration) relationships to the 1-min averages for about 2 hr when under the influence of these storms. Pertinent data are provided in Table 10. The lowest anemometer for Brookhaven is 37 ft above the ground as compared to heights ranging from 10 to 25 ft for the operational data, but mean gust factors from the Brookhaven observed hurricanes are slightly greater than for the tropical storms summarized in Table 9. Also, the mean 2-sec gust factors for Carol were virtually the same as for Edna, although Carol's speeds were considerably stronger. Since the Brookhaven tower is surrounded by a scrub pine forest reaching up to 30 ft, the anememeter height of 37 ft is not comparable to heights of the operational weather station anemometers which are mostly over open airports. Apparently there is enough difference in gustiness with synoptic situation and local terrain to

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21. Smith, M.E. and Singer, I.A. (1956) Hurricane Winds at Brookhaven National Laboratory, Brookhaven National Laboratory, unpublished study.

Table 8. Probable (50 percent) Gust Factors for 20- to 80-mph Average Hourly Speeds Using Durst's[8] Model

Mean Hourly Speed (mph)	Mean Hourly Speed (knots)	Gust Factor (GF) 600 sec	60 sec	30 sec	20 sec	10 sec	5 sec
20	17	1.05	1.25	1.30	1.35	1.40	1.50
30	26	1.07	1.23	1.33	1.37	1.43	1.47
40	35	1.07	1.25	1.32	1.35	1.42	1.48
50	43	1.06	1.24	1.32	1.36	1.42	1.48
60	52	1.07	1.24	1.32	1.35	1.42	1.48
70	61	1.06	1.24	1.31	1.36	1.41	1.49
80	69	1.06	1.24	1.33	1.36	1.43	1.48

Table 9. Comparison of 2-sec Gust Factors During 1-min Winds of 20 to 59 knots in Tropical and Extra-tropical Storms, Anemometer Height 10 to 25 ft

Storm Type	No. Observ.	Gust Factor Mean	Gust Factor Standard Dev	Percentile Values 50	75	90	98
Tropical	107	1.36	0.133	1.34	1.42	1.49	1.76
Extra-tropical	79	1.31	0.116	1.29	1.39	1.47	1.61

Table 10. Mean 2-sec Gust Factors in 1-min Winds for Hurricanes Carol and Edna (Smith and Singer[21])

Height (ft)	Carol *Speed (knots)	Carol Gust Factor	Edna *Speed (knots)	Edna Gust Factor
37	28	1.43	23	1.45
75	36	1.38		
150	47	1.28	28	1.29
355	52	1.22		
410			39	1.18

*Mean of all 1-min average speeds for the period studied, about 2 hr.

obscure a conclusion on the relative turbulence of tropical and extra-tropical storms.

Recorder charts of steady winds greater than 70 knots are scarce and "withstanding" windspeed criteria can well exceed this value. Data for Mt. Washington, compiled from recorder charts in 1958 by AFCRL's M. Gutnick for an unpublished study, were utilized to extend the speed range. This source provided 26 observations of gust factors for 5-min steady winds ranging from 71 to 163 knots. Another input are four values derived from wind data taken during hurricanes that passed close to the Blue Hill Observatory, near Boston, Mass. These inputs are discussed further in the next section.

3.3 Development of Gust Factor Relationships

Our purpose in this part of the study is to establish a relationship between expected gust and the steady windspeed, regardless of location. Since there is a wide range of exposure conditions and instrumentation in the 548 operational, 26 Mt. Washington and 4 Blue Hill wind maxima, it was decided that the most representative relationship of the gust to the average speed would be that obtained from using all the data and applying it to the average anemometer height from which the data were taken, approximately 50 ft.

The form of the relationship between the gust factor and the steady wind poses another problem. A straight line regression curve would provide a fair approximation of the expected decrease in gust factor with increasing speed; however, it would imply that at some speed, perhaps between 150 and 200 knots, expected gustiness becomes zero. Logic implies that the true relationship is a curve asymptotic to a gust factor of 1.0, so that there is expectancy of some gustiness no matter how strong the speed. This is in general agreement with findings of turbulence in the upper air. At jet stream levels of 30- to 40-thousand ft, aircraft research by Endlich and McLean[22] show gusts running 5 to 20 fps (3 to 12 knots) with a peak gust of 37 fps (22 knots) when there is measurable turbulence. The average jet stream core speed is 240 fps (142 knots), but speeds approaching 338 fps (200 knots) with turbulence have been encountered. The gust factor at such extremes is evidently about 1.1 when there is turbulence, but the expected factor must be closer to 1.0 since measurable turbulence was observed only about 30 percent of the time during research in the jet stream.

To obtain a more realistic solution, a least squares relationship in which the gust factor, GF, approaches unity with increasing 5-min speed was developed.

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22. Endlich, R.M. and McLean, G.S. (1965) Jet stream structure over central United States determined from aircraft observations, J. Appl. Meteorol. 4(No. 1):83-90.

The resulting equation takes the form

$$GF = 1 + Ae^{-BV} \tag{1}$$

where A and B are constants and the speed of the steady wind, V ($\geq$ 20 knots), is taken to be the 5-min average. This implies a gust factor of 1 plus A when the 5-min speed is truly zero, but this relationship was not designed to be applicable below the range of data used, 20 knots.

Figure 3 shows the median (50 percentile) gust factors (taken from Table 7) versus class interval midpoints of 25, 35, 45, 55, and 65 knots, the 2-sec GF curve $GF = 1 + 0.55\,e^{-0.0093V}$, and a 30-sec GF curve subjectively drawn. Also included are two points of median gust factor for the Mt. Washington winds, one for 11 observations ranging from 71 to 89 knots, and the other for 15 observations ranging from 92 to 188 knots. The Blue Hill point includes four values with a speed range of 73 to 105 knots.

A study of Figure 3 indicates that although the Mt. Washington points do not quite follow the pattern of decreasing gust factor as speed increases, the small decrease (from 1.19 to 1.23) does not appear significant. Also, the Blue Hill data point does not help in establishing this pattern, probably because two observations for the September 1938 hurricane are based upon passage of miles of wind over a 3-cup anemometer which did not have modern few-second response recorders. These values were obtained from notes made by the observer. Since the Blue Hill

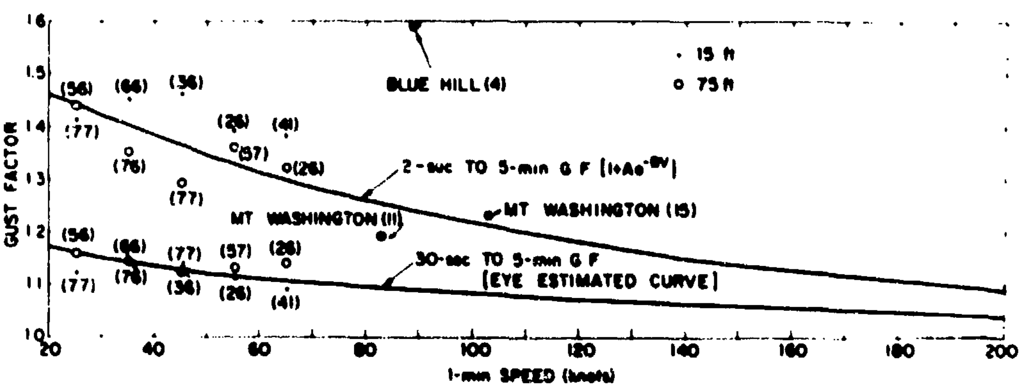

Figure 3. Median Values of the Gust Factor for 5-min Steady Speeds, the 2-sec GF Curve, $GF = 1 + 0.55e^{-0.0093V}$, and a 30-sec GF curve subjectively drawn (number of observations for each point is shown in parenthesis)

average is based on much less data than the other points, it may not be representative of the true average.

The constants and parameters giving statistical representativeness for the entire sample of and various selections of the data are shown in Table 11. Also shown are the gust factors for 5-min speeds from 25 to 200 knots which were computed from the relationships derived for the sample. There is little difference between the values obtained with all 578 observations (column I) and the same sample excluding the four questionable Blue Hill observations (column II). The F-ratio for significance shows both fits are very highly significant, but

Table 11. Distributions of the 2-sec Gust Factor (GF) to the 5-min Steady Speed Calculated From a Least Squares Fit to: $GF = 1 + Ae^{-BV}$

	Samples*				
	I	II	III	IV	V
Sample size, n	578	574	548	260	248
Constant, A	0.55	0.56	0.61	0.59	0.62
Constant, B	0.0093	0.0102	0.0122	0.0116	0.0115
Standard error, SE	0.45	0.44	0.44	0.44	0.43
Coef. of Correl., r	0.35	0.38	0.34	0.31	0.35
F-ratio	81	95	69	27	34
	Gust Factors				
5-min Steady Speed V(kts)	GF	GF	GF	GF	GF
25	1.44	1.43	1.45	1.44	1.47
35	1.40	1.39	1.40	1.39	1.41
45	1.36	1.35	1.35	1.35	1.37
55	1.33	1.32	1.31	1.31	1.33
65	1.30	1.29	1.28	1.28	1.29
75	1.27	1.26	1.24	1.25	1.26
100	1.22	1.20	1.18	1.18	1.20
125	1.17	1.17	1.13	1.14	1.15
150	1.14	1.12	1.10	1.10	1.11
175	1.11	1.09	1.07	1.08	1.08
200	1.09	1.07	1.05	1.06	1.06

*Samples:
I. All data from operational anemometers plus Mt. Washington and Blue Hill.
II. All data except Blue Hill.
III. Operational anemometers only.
IV. Operational anemometers at 75 to 95 ft.
V. Operational anemometers at 10 to 28 ft.

exclusion of the Blue Hill values raises the F-ratio from 81 to 95. The values obtained using all 548 operational anemometer data, the 260 observations from operational anemometers between 75 and 95 ft, and the 248 between 10 and 28 ft, are shown in columns III, IV and V, respectively. Forty observations, 30 at 56 ft and 10 at 58 ft, of the 548 observations in the distributions of Tables 3, 4 and 6 were omitted from columns IV and V. There is little difference between the results for higher and lower anemometers, justifying application of the expression to all observations of the steady winds of the climatological distributions selected for "operational" and "withstanding" extremes. The tendency for gust factors to be smaller at greater heights, especially as speed increases (as shown by the mean and standard deviations of gust factors in Table 6), is mostly masked out by the least squares regression.

The relatively small correlation coefficients (Table 11) clearly depict the great variability of gustiness from one situation and place to another. It appears desirable to settle on one relationship between 5-min windspeeds and 2-sec gusts; that relationship is probably best depicted by Eq. (1) and the values under column I in Table 11. Selecting column I values over column II values avoids any arbitrary discarding of available data. It also provides some conservatism since gust factors at extremely high windspeeds will be in the same "ball park" as is implied from the jet stream turbulence encounters of aircraft at comparable high windspeeds in the free air. The curve for the 2-sec gust shown in Figure 3 is for the constants A and B given in column I, Table 11.

A tool to obtain gusts of other durations which would be applicable to the various downwind dimensions shown in Table 1 is still required. To develop this, the general assumption that the gust factor diminishes logarithmically with increasing duration, as in Figure 2, was accepted, but it was recognized that the relationship is not exact and details providing departures from it would be desirable. As a first step the 2-sec factors were computed from Eq. (1) and column I, Table 11. These are listed in Table 12. The next step was to plot the median (50-percentile) values of the 30-sec GF from Table 7 on Figure 3. A curve was fitted by eye to the remaining points, resembling the 2-sec curve, but with a much smaller slope since the range of ratios of 30-sec to 5-min winds is so much lower than 2-sec to 5-min. Gust factors for the 30-sec wind selected from this curve are shown in the second column of Table 12. The values in Table 12 are plotted on Figure 4. It permits one to estimate, as a function of the 5-min speed a most-probable gust for various durations between 2-sec and 5-min. As has been indicated, much of the recent wind summaries contain steady winds that are 1 min averages; consequently, gust factors are required for these 1-min steady speeds. Gust factors for 2-sec gusts in 1-min wind speeds can be estimated by dividing the 2-sec gust factors for 5-min winds by the 60-sec gust factors for

Table 12. Gust Factors With Respect to the 5-min Steady Speed. The 60-sec GF was estimated from Figure 4, the 30-sec GF was estimated from Figure 3, and the 2-sec GF was derived from Eq. (1)

5-min Speed (knots)	Gust Factor (GF)		
	60-sec	30-sec	2-sec
20	1.120	1.172	1.4566
30	1.105	1.151	1.4160
40	1.094	1.134	1.3791
50	1.085	1.121	1.3454
60	1.077	1.111	1.3147
80	1.066	1.095	1.2613
100	1.057	1.081	1.2170
125	1.049	1.069	1.1719
150	1.042	1.059	1.1363
175	1.035	1.050	1.1080
200	1.028	1.040	1.0856

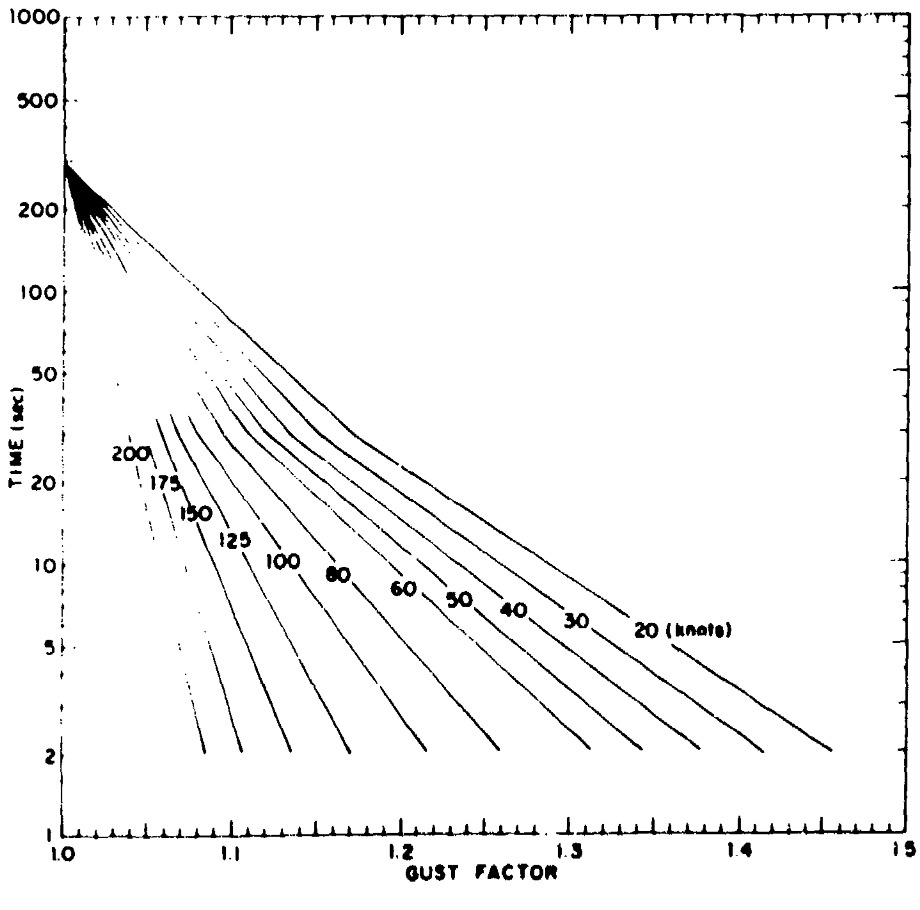

Figure 4. Expected Gust Factors Versus 5-min Steady Windspeed

Table 13. Gust Factors With Respect to the 1-min Steady Speed. The 30-sec GF was calculated using the ratio of the 30-sec to the 60-sec GF values given in Table 12. Similarly, the 2-sec GF was calculated using the ratio of the 2-sec to the 60-sec GF values in Table 12.

1-min Speed (knots)	Gust Factor (GF) 30-sec	2-sec
20	1.0464	1.3005
30	1.0416	1.2814
40	1.0365	1.2606
50	1.0331	1.2400
60	1.0315	1.2207
80	1.0272	1.1832
100	1.0227	1.1513
125	1.0190	1.1172
150	1.0163	1.0905
175	1.0144	1.0705
200	1.0116	1.0560

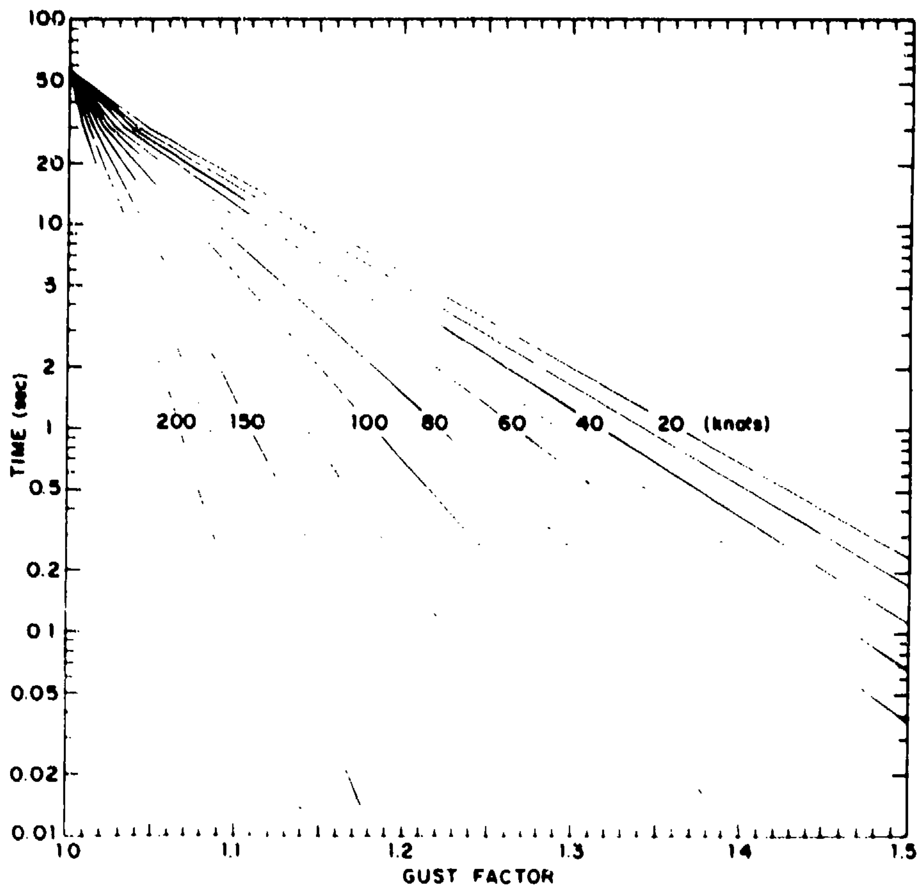

Figure 5. Expected Gust Factors Versus 1-min Steady Windspeed

5 min, both in Table 12. These values are provided in Table 13. Analogous 30-sec values, obtained by dividing the 30-sec gust factors by the 60-sec gust factors are also presented in Table 13. igure 5 is a plot of the values in Table 13. It provides a tool for estimating gust factors for durations down to less than a tenth of a second.

The value of the gust factors obtained using Figures 4 and 5 is the best estimate of a gust to use for a windspeed which has a specific risk, considering the many locations and synoptic situations typical of exposure of military equipment. In some cases gusts will be higher, in others, lower, but the probability of a 2-sec gust using these gust factor relationships will thus be about the same as the steady speed decided upon.

3.4 Additional Considerations

The emphasis in this report has been placed on the most common wind conditions; however, there are other locally prominent situations for which general applications would be unreliable. Wind flow in the lee of mountains represents one such situation. These occur frequently during the winter months along the eastern foothills of the Rocky Mountains and other areas of the world (Julian[23] and Lovill[24]) where moderately strong winds at low altitudes run into mountain barriers. Wind recorder charts during the storms of 16 January 1967 and 7 January 1969 at the National Center for Atmospheric Research (NCAR), Boulder, Colorado were reproduced in the NCAR Quarterly (Spring 1967 and May 1969). Steady winds were nearly 50 mph (43 knots) for several hours while peak gusts were 110 to 125 mph (96 to 109 knots). It was not possible to resolve 1- or 5-min velocities due to the slow speed of the recorder, but the gust factors, frequently greater than 2.00, were considerably higher than any other strong winds studied. This extreme gustiness from a lee wave in the foothills of a mountain barrier seem far more severe than gustiness on an isolated mountain peak, such as Mt. Washington, where steady winds are more severe. Designing military equipment to withstand such gust factors is not required, since gusts as strong as these are obtained with the lower gust factors at higher steady winds available from the climatology of typical windy areas.

Terrain differences can also produce large variations in windspeed. For example, Santa Ana and Newhall winds of California occur when northly winds

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23. Julian, L. T. and Julian, P. R. (1969) Boulder's winds, Weatherwise 22(No. 3).

24. Lovill, J. E. (1969) Transport Processes in Orographically Induced Gravity Waves as Indicated by Atmospheric Ozone, Atmospheric Science Paper No. 135, Colorado State University, Fort Collins, Colorado.

are channeled into mountain passes and valleys with a resultant increase in velocity (Koutnick[25]). Similarly, a change in wind gustiness can accompany a change in wind direction. One such occurrence seems to be present in the data sample used for this report. Figure 6 illustrates this change which occurred during a typhoon at Kadena AB, Okinawa. As the storm approached, between

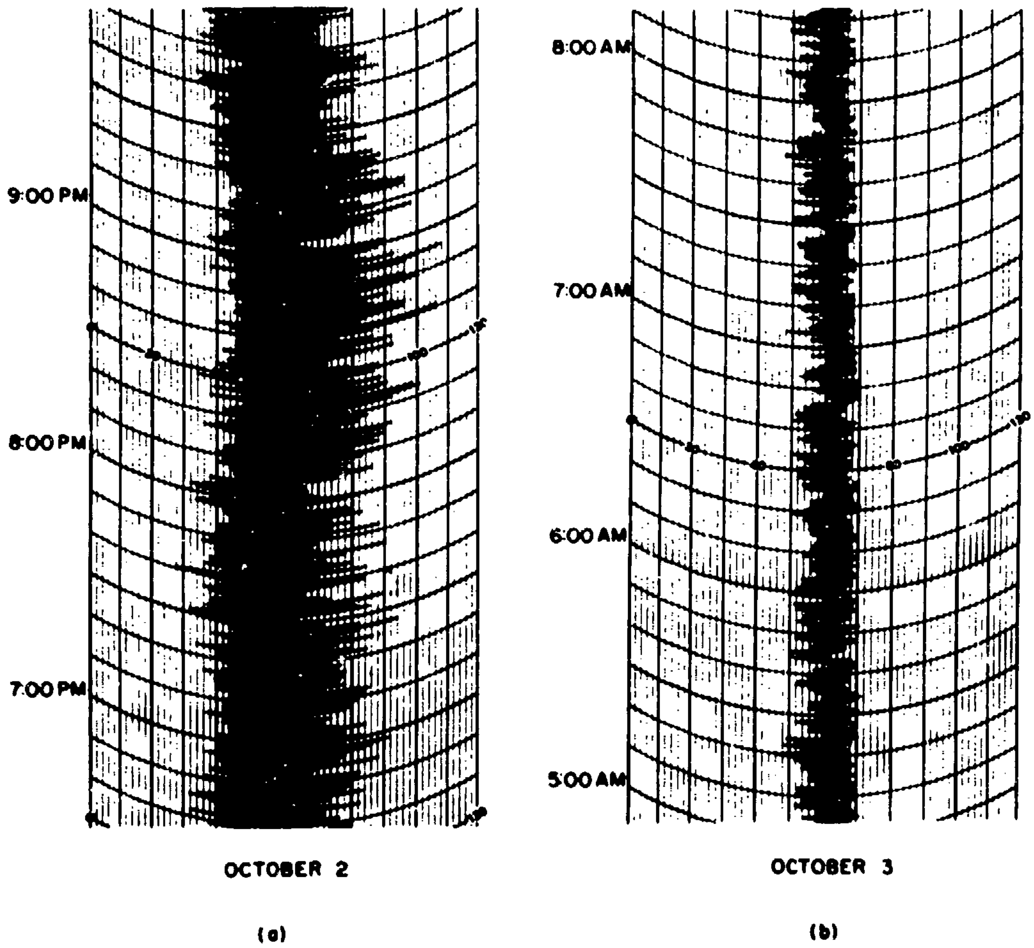

Figure 6. Windspeed Record (knots) During a Typhoon at Kadena AB, Okinawa, 2-3 October 1961. Figure 6(a) was taken with a NE wind as the storm approached, and Figure 6(b) was taken after the wind had gradually veered to the SSE when the center of the typhoon had passed

25. Koutnick, W. (1968) Newhall winds of the San Fernando valley, Weatherwise 21(No. 5):186.

2000 and 2100 hr on 2 October 1961, the winds were out of the northeast and very gusty; the mean 5-min speed was 60 knots and the mean gust factor was 1.62. When the center of the typhoon passed, the wind direction gradually veered to the SSE and by 0600 to 0700 hr on 3 October 1961, although the mean windspeed was still very strong, 63 knots, the strong gustiness was not longer present—the mean gust factor had dropped to 1.11. Wind records at nearby Futema MCAF, Okinawa during the same hurricane do not indicate any reduction in gustiness such as shown in Figure 6. Since no reference to instrument damage was made on the recorder chart, it appears that orographic differences were the probable cause.

4. BEHAVIOR OF EXTREME WINDSPEEDS AND GUSTS WITH HEIGHT

A major problem with pooling the various inputs of wind data was the determination of the best method for adjusting windspeeds to a common height. Once this relationship was established, it could then be used to describe windspeed and gusts over the vertical extent of use of military equipment.

Wind flows in response to a difference in pressure in the atmosphere. These pressure gradients change slowly with altitude, and so for practical purposes, the changes within the layer for which equipment must be designed is negligible; yet changes in speed with height through this layer are known to be quite great because air motion near the surface does not obey the pressure gradient law. Anemometers near the ground may be hardly turning, whereas those on tall buildings and towers may show moderately strong, gusty winds; kites may be difficult to launch, but once several hundred feet high, they fly without difficulty. Friction caused by terrain is one of the main factors affecting the vertical gradient of the wind up to an altitude at which friction is considered negligible, the gradient level. At this height, 1 or 2-thousand ft, the pressure gradient is said to be dynamically balanced against two components involving rotation: (1) that of the rotation of the earth; and (2) the curvature of the wind path. A theoretical wind can be computed for isobars on a surface weather map which quite closely corresponds to observed winds at the gradient height.

The height of the gradient level and the velocity profile of the wind up to that level can vary greatly, mainly due to the type of surface and the stability of the air. Stability is chiefly a function of the temperature structure in the boundary layer which can range from a super-adiabatic lapse rate (temperature decreasing with altitude so sharply that air displaced upward will continue upward because it is warmer than its surroundings), to a negative lapse rate or inversion (temperature increasing with height and consequently air displaced upward is cooler than its surroundings and tends to sink back to its original level).

The inversion is a very stable situation during which fog and pollution is often present. A neutral condition (adiabatic) is said to exist when the temperature lapse rate is such that a parcel of air, displaced vertically, will experience no buoyant acceleration. This report is concerned with the relationship during which very strong speeds occur at the surface and for which equipment must be designed to operate. In general, a neutral (adiabatic) lapse rate is established by the turbulent mixing caused by these strong winds at the surface, simplifying the problem of arriving at the most typical windspeed profile for very high speeds.

Basic equations for specifying windspeed and direction with altitude in the boundary layer, originally developed for ocean depth, is termed the Ekman Spiral. However, micrometeorologists who have been studying the energy transfer and diffusion phenomena in the boundary layer, have found various empirical relationships which fit windspeed data gathered at various heights above the ground. Two general relationships, a logarithmic and a power law, have been used. For thick layers (when heights are between several meters and about 300 m), wind profiles tend to obey a power law (DeMarris,[26] Johnson,[27] and Munn[28]). This relationship is normally used when neutral stability exists. The power law is the form

$$V/V_o \quad (H/H_o)^p \tag{2}$$

where V_o is the windspeed at some reference level, H_o, and V is the windspeed at the desired level, H. The exponent, p, is dependent on the atmospheric temperature lapse rate, windspeed and, to a lesser extent, on ground roughness.

The exponent, p, averages between 0.1 and 0.3, but can range from near zero to about 0.8. It is larger under a stable vertical temperature gradient and smaller for neutral and unstable conditions; it decreases with increasing windspeeds and increases somewhat with terrain roughness (DeMarrais[26]). The typical value used for p is 1 7 (equal to 0.143) (Sherlock[16]). Early workers had already recognized that this p value was applicable to typical steady or mean winds but not applicable to gustiness, and Sherlock noted that gusts were better described with a value of p 0.0625. Shellard,[3] in reducing high windspeeds and gusts to a common height of 33 ft, used the power-law relationship with a p value of 0.17 for mean speeds and 0.085 for gusts.

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26. DeMarris, G.A. (1959) Wind-speed profiles at Brookhaven National Laboratory, J. Meteorol. 16(No. 2):181-190.

27. Johnson, O. (1959) An examination of vertical wind profile in the lowest layers of the atmosphere, J. Meteorol. 16(No. 9):144-148.

28. Munn, R.E. (1966) Descriptive Micrometeorology, Advances in Geophysics, Academic Press, New York and London.

It is difficult to determine appropriate p values for extreme speeds because the majority of studies of wind profiles are made under regimes of light to moderate windspeeds; therefore, p values resulting from such studies may not be applicable to extremely high windspeeds.

In one of the most recent reviews of this problem, Davenport[5] introduced the topic with the following summary of the average p values and also the average height above the ground of the gradient wind.

	p	Gradient Height (ft)
Flat open country	0.16	900
Rough wooded country, city suburbs	0.28	1300
Heavier builtup urban centers	0.40	1400

Since Davenport is most concerned about design of large buildings and structures, he also presented p values obtained from cities all over the world based upon observations at different heights up to 1250 ft. These values are generally 0.3 to 0.4 and, if applied to anemometer heights of the data sample studied herein to obtain operational and withstanding extremes, could lead to considerable gradient in the vertical of the mean or steady windspeeds. The reason for this is that they must show the increase such that the gradient which is attained at the gradient level will be the same as in the surrounding open country. Since the winds in the lower boundary layer in the cities will be much weaker because of the blocking of the buildings, a very large increase with height must be shown. In fact, Davenport provides a comparison of maximum windspeeds on tall city buildings with those from much lower anemometers of neighboring airports. The airport speeds are considerably higher. Our problem is to arrive at the correct p values for flat and open country when very strong steady winds are being encountered and for the various gust durations found applicable to equipment.

To get a better appreciation of the problem, a special study was made with research data obtained by AFCRL's Boundary Layer Branch (LYB) in connection with diffusion and energy-transfer research. The study is summarized in Appendix B. As noted therein, the surrounding terrain was flat and unobstructed. Unfortunately, steady speeds up to only about 25 knots were obtained, considerably lower than the values needed in establishing extreme windspeed relationships.

Figure B1 in Appendix B describes the pattern of decreasing p values as steady speed increases and gust duration decreases as noted by Sherlock.[16] Except for the decrease of p with increasing windspeed, these values support the practice in the United Kingdom of applying mean hourly windspeeds of anemometers to other heights utilizing a p value of 0.17, and using a p value of 0.085 for a 3-sec gust.

Since our chief concern is how wind and gust varies during exceptionally strong winds, no conclusions as to the appropriate p values can be made on the material provided thus far. Unfortunately, there are few micrometeorological research data available under such extremely strong wind conditions. Smith and Singer[21] studied continuous wind recordings at four levels in one case and three levels in another to altitudes of roughly 400 ft during the passage of two hurricanes near micrometeorological towers at Brookhaven, New York. One-minute averages and 2-sec gusts were obtained continuously for about 20 hr in each case.

Table 14 has been prepared from the mean 1-min and mean peak gust data. It shows the p values very much higher than were expected when the heights used in the power expression are those of the anemometer above the ground. A review of the situation indicated that the meteorological data tower is surrounded by scrub pine with an average height of 30 ft. Therefore, the p values obtained with 30 ft subtracted from the actual anemometer heights has also been included in Table 13. These are much closer to the typical values suggested for flat areas; however, differences are not as great as would be expected, especially on the basis of the Sherlock, Shellard, and Gringorten data which are for nominal speeds. No explanation can be provided.

One of the best sources of high wind speed data at various levels was the Argonne National Laboratory Fifteen-Year Climatological Summary (Moses and Bogner[29]). Table 87 in that summary contains the maximum windspeed (gust) recorded each month from 1 January 1950 through 31 December 1964 at the 19- and 150-ft levels of their meteorologically instrumented tower in Argonne, Illinois. Gust speeds up to 62 mph were recorded at 19 ft, and up to 86 mph at

Table 14. Power Law Exponent, p, for Hurricanes Carol and Edna (based on 2 hr of 1-min and 2-sec speeds measured at the Brookhaven Laboratory, N.Y.) Values in parentheses obtained when average height of surrounding scrub pine, 30 ft, is subtracted

	Carol		Edna	
	37/355 ft	(7/325 ft)	37/410 ft	(7/380 ft)
Average of 1-min Speeds	0.310	(0.182)	0.326	(0.197)
Average of Max. 2-sec Speed-per-Minute	0.233	(0.137)	0.236	(0.142)

29. Moses, H. and Bogner, M.A. (1967), Fifteen-year Climatological Summary, January 1, 1950-December 31, 1964, Argonne National Laboratory, DuPage County, Argonne, Illinois, ANL-7084, Argonne National Laboratory, Argonne, Illinois.

150 ft. In private communications with Mr. Moses and his co-workers, we determined that only three of the 180 monthly maximum wind pairs did not occur on the same day. For the remaining 177 pairs the exponent, p, was determined from the wind profile power law

$$V_{19}/V_{150} = (19/150)^p$$

where V_{19} and V_{150} are gust speeds observed at 19 and 150 ft, respectively. Figure 7 shows the computed p values plotted against the 19-ft windspeed for the 177 pairs. The dispersion of p values for a given speed is quite large; however, the average p values plotted by 5-mph increments (the x's) decreases relatively smoothly for 19-ft gust speeds up to 55 mph. Such a wide spread of the data signifies that the derived relationship may be valid in the mean, but could have poor correlation in individual cases.

Figure 8 is a separate plot of the mean p values with the sample size for each category shown next to each point. Following the general decrease in p values with increasing wind speed up to 55 mph, there is a sharp increase in p for the two highest windspeed intervals. It cannot be determined if this unexpected increase is real or if it is the result of the small sample size at the higher speeds. The relative dispersion of p values around the plotted means is indicated by the standard deviation by 5-mph intervals (the dot-dash curve on the left).

Also shown in Figure 8 are the curves of best linear fit (correlation coefficient $r = -0.20$) and best quadratic fit ($r = 0.29$) to the total data sample. Equations for the curves are:

$$p = 0.164 - 0.00118\, V_{19} \tag{3}$$

and

$$p = 0.388 - 0.0120\, V_{19} + 0.000127\, V_{19}^2 . \tag{4}$$

The linear equation has the drawback of a zero p value at about 140 mph, becoming negative at higher speeds, a result that is neither logical nor borne out by measurements. Although the quadratic equation appears to fit the data better and has a higher correlation coefficient, there is no physical reasoning to support a continuously increasing exponential value with increasing windspeed at speeds greater than 47 mph. It was decided that the best compromise is to fit a hyperbola to the data, depicted in Figure 9, forcing p to infinity as the 19-ft gust speed

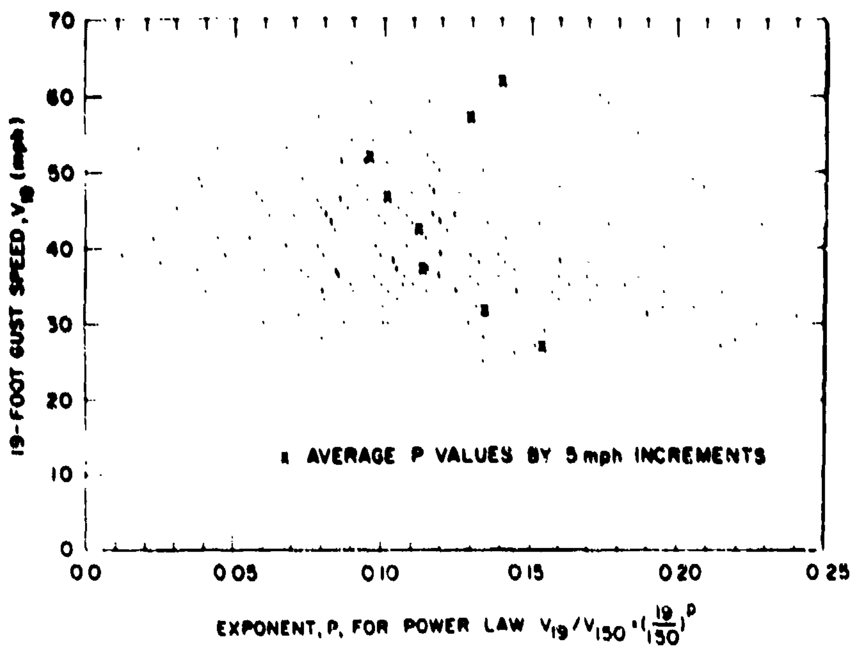

Figure 7. Distribution of p Values for Gust Speeds Measured at 19 and 150 ft

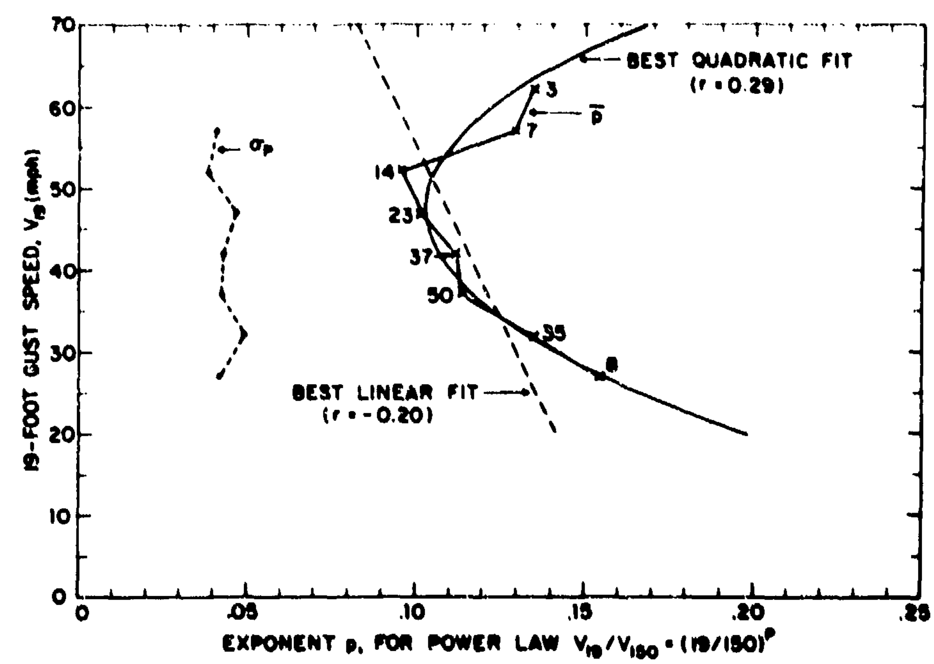

Figure 8. Means and Standard Deviations by 5-knot Intervals of the 19-ft Speeds for the Data in Figure 7; also best linear and quadratic fit to that data

approaches zero and allowing the data to determine the best vertical p asymptote. The resulting equation is

$$p = 0.77 + 1.56/V_{19} \tag{5}$$

where the limiting p value approaches 0.077 as V_{19} (mph) becomes very large; however, the correlation is still quite low, 0.23, due to the dispersion of the data points. This p value is close to the value Sherlock[16] suggested, 0.0625, in conjunction with gusts.

The Argonne National Laboratory also observed gust speeds at the 75-ft level on their instrumented tower, but did not tabulate the maximum monthly speed at this level. In a private communication, we obtained a few gust maxima for the 75-ft level, five of which could be matched (within 3 min) to maximum gusts at the 19- and 150-ft levels listed in Argonne's Table 87 (Moses and Bogner[29]). Computed p values for various levels are shown in Table 15 (19-ft windspeeds ranged from 52 to 64 mph).

Specific conclusions cannot be drawn from the previous small sample. It illustrates how the p value is highly variable and is dependent upon both the altitude increment and its height above ground. Consequently, generalized values for the entire boundary layer may not even be applicable to the height of most standardized military equipment which will not extend more than a few hundred feet.

Table 99 of the Argonne National Summaries presents a percentage frequency of p values versus the 10-min averaged windspeeds measured at 19 ft. The period of record for this Table is 1 January 1961 through 31 December 1964. It contains about 35,000 hourly observations. For 19-ft windspeeds greater than 24 mph (the highest speed class interval presented), the median p value is about 0.125. Based on this information, it was decided that for converting all windspeed data in this report to common heights, the power-law relationship will be accomplished with p values of 0.125 for 1-min mean speeds up to 50 knots which will be shown to be applicable to operations. A value of 0.080 will be used for 1-min mean speeds greater than 50 knots (applicable to "withstanding" extremes) as well as for all gust speeds. The appropriate conversion factors are presented in Table 16.

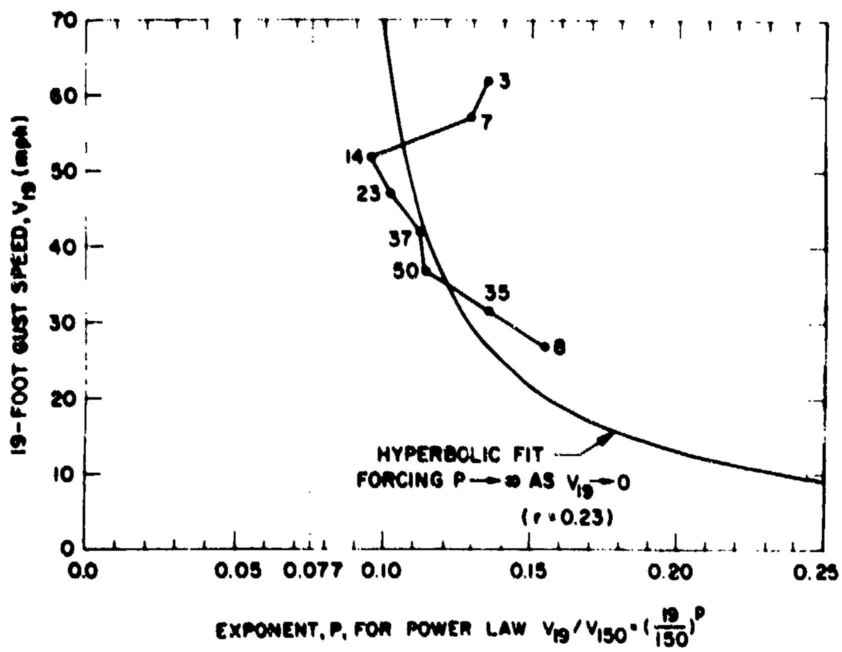

Figure 9. Hyperbolic Fit to Data in Figure 7, Forcing p to Infinity as the 19-ft Gust Speeds Approach Zero

Table 15. P Values for Five Cases Between 19-, 75-, and 150-ft levels

	Between 19 and 75 ft	Between 75 and 150 ft	Between 19 and 150 ft
29 August 1955	0.1398	0.2125	0.1642
4 July 1957	0.0653	0.1375	0.0895
27 March 1961	0.1650	-0.0395	0.0964
30 April 1962	0.2062	0.1500	0.1874
19 June 1964	0.2004	0.1225	0.1742
	Mean: 0.1553	0.1166	0.1423

Table 16. Factors to Convert Wind Speeds at 10 ft Above Ground to Wind Speeds at other Heights Based on the Power Law Relationship $V_H/V_{10\ ft} = (H/10ft)^P$ (Use reciprocal factors to convert from height H to 10 ft)

Height ft	(meters)	P = 0.125*	P = 0.080 **
5	(1.5)	0.917	0.946
10	(3)	1.000	1.000
20	(6)	1.090	1.057
30	(9)	1.147	1.092
40	(12)	1.189	1.117
50	(15)	1.223	1.137
75	(23)	1.286	1.175
100	(30)	1.334	1.202
125	(38)	1.371	1.224
150	(46)	1.403	1.242
200	(61)	1.454	1.271
250	(76)	1.500	1.294
300	(91)	1.530	1.313
350	(107)	1.560	1.329
400	(122)	1.586	1.343
500	(152)	1.631	1.367
600	(183)	1.668	1.388
700	(213)	1.701	1.405
800	(244)	1.729	1.420
900	(274)	1.755	1.433
1000	(305)	1.778	1.445

* For use with 1-min steady wind speed up to 50 knots.

** For use with 1-min steady wind speed greater than 50 knots as well as for all gust speeds.

5. WIND EXTREMES APPLICABLE TO DESIGN FOR WORLDWIDE OPERATIONS AND WITHSTANDING

Unless otherwise noted, windspeeds in this section will apply to a height of 10 ft above ground. All data used were reduced to that height using the power-law relationship described in Section 4. The factors in Table 16 can be used to convert the 10-ft winds to other heights.

Directly recorded data for record wind extremes are very rare due to damage or destruction of the wind measuring instruments, power outages, etc., during the event. After the passage of severe weather phenomenon such as tornadoes, typhoons and hurricanes, there are numerous reports in the newspaper or other media, of very high wind speeds (up to 200 mph), but attempts to obtain the meteorological records substantiating such reports invariably indicate that the speeds had been estimated, perhaps exaggerated. These estimates have sometimes been calculated from the amount of force required to blow over a building or tree, to overturn an automobile or to drive a metal rod through a wooden post. Since the reliability of such reported speeds are unknown, they have not been used in this report. Even estimates from meteorological sources have been excluded unless the speeds were at least observed on a visual indicator, if they were not actually recorded.

5.1 Record Wind Extremes

Since the policy for MIL-STD-210B is that extremes be applicable to general areas rather than specific point-type locations, mountain-peak windspeeds, tornadoes and orographic funneling situations have been excluded. A few outstanding examples of these are presented in this section for general background. If the designer expects his equipment to be used in such locations, a special wind study should be tailored for the installation.

The recognized worldwide maximum windspeed measured at a surface station is a 5-min speed of 188 mph (163 knots) and a 1-sec gust of 231 mph (201 knots) measured at the Mt. Washington, N.H. Observatory on 12 April 1934. These were later corrected to 204 mph (177 knots) and 225 mph (195 knots) respectively (Pagluica et al[30]). The Mt. Washington Observatory is 6262 ft above MSL and the anemometer was mounted at 38 ft.

Mt. Fuji, Japan (Elevation 12,375 ft) is also known for its windiness. In a 23-year record, a maximum 30-min windspeed of 141 knots was observed in 1942. Gust speeds were unavailable from this location.

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30. Pagluica, S., Mann, D.W., Marvin, C.F. (1934) Monthly Weather Review 62:38.

Tornado winds also are excluded from military design criteria because they are considered to be too localized. No wind measuring device has ever survived the full fury of a tornadic wind, although speeds up 120 mph have been observed in close proximity to tornadoes. Some authorities have suggested that winds could exceed 300 mph (Huschke[31]). It has been estimated that winds in localized regions of the funnel may reach peak speeds close to the speed of sound (Battan[32]).

5.2 Highest Recorded Winds Applicable to MIL-STD-210B

Excluding the Mt. Washington extremes, the highest known windspeed was a 180-knot gust observed (on a visual readout) at Thule AFB, Greenland during a severe arctic storm in March 1972 (Stansfield[33]). The gust was measured by an Aerovane anemometer mounted on top of a phase shack (shelter hut) at a height of about 30 ft, with a remote readout indicator at a BMEWS site. The phase shack is located at the base of the Greenland Icecap in a valley between two small mountain ranges leading to Baffin Bay. The additional speed due to the gravitational downslope flow of the ice-cap air mass being funneled into a valley makes such a location ideally suited for sustaining exceptionally high windspeeds as severe cyclones (often exceeding hurricane intensity) move northward over Baffin Bay. It was in such a storm that the phase shack experienced winds of 120 knots or greater for 4 hr during which the record gust of 180 knots was observed. It is of interest to note that at Thule AB (located in the same valley, only 5 n mi away), a maximum gust of only 96 knots was observed during the storm. This example emphasizes the extreme variability which can occur over short distances.

The maximum gust speed that has been recorded is 152 knots (height, 30 ft, corresponding to 139 knots at 10 ft). It occurred during a typhoon that passed over Iwo Jima AB, Volcano Islands in 1948. The maximum recorded sustained wind is a 5-min speed of 131 knots measured at a height of 54 ft (corresponding to 119 knots when corrected to a 1-min speed at 10 ft) at San Juan, Puerto Rico. However, a wind of this magnitude appears to be an extremely rare occurrence for San Juan. In a 69-year record, the next highest annual 5-min sustained winds were only 104, 78, 70 and 61 knots.

The extremes cited above should not be considered the highest winds that have occurred. Higher speeds most certainly have occurred, but they merely

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31. Huschke, Ralph E. (Editor) (1959) Glossary of Meteorology. American Meteorological Society, Boston, Massachusetts.

32. Battan, L.J. (1961) The Nature of Violent Storms, Anchor Books, Doubleday & Co., Inc., Garden City, New York.

33. Stansfield, J.R. (1972) The severe arctic storm of 8-9 March 1972 at Thule Air Force Base, Greenland Weatherwise 25(No. 5):228-233.

have not been recorded due to their devastating damage or absence of wind instrumentation.

The highest windspeeds affecting sizable areas occur within typhoons that pass over the islands of the Western North Pacific Ocean. Of these, Typhoon Nancy was the most intense typhoon ever observed by the Joint Typhoon Warning Center (JTWC) since its inception in 1945. During the peak intensity of Typhoon Nancy, there were five consecutive air reconnaissance observations during the period 0230 Z, 10 September to 1630 Z, 12 September 1961, each of which indicated reliable estimated maximum surface winds of 200 knots. However, the total analysis of the storm must have indicated a somewhat lesser intensity because the JTWC officially reported the maximum surface winds to be 185 knots from 11 1200 Z to 12/0600 Z (JTWC[34]).

Windspeeds determined by aerial reconnaissance are considered to be steady winds with averaging times corresponding to a duration of several minutes. One of the primary methods used for estimating surface windspeeds is from the state of the sea, such as size and number of white caps, color, etc. Other methods incorporate measurements from doppler radar and sea-level pressure measuring dropsondes. This latter technique was probably used for the 200-knot estimates cited above since, in such an intense storm, low-level penetrations needed to determine the state-of-the-sea are not made.

For documentation, it is assumed that the highest sustained wind speed affecting a sizable area of military concern was the 185 knots (sustained for a duration of several minutes) that was calculated during Typhoon Nancy. Assuming this to be a 5-min steady wind, the most probable 2-sec gust expected to accompany this sustained wind would have been 204 knots.

5.3 Operational

Military equipment sensitive to wind forces, such as ships, and aircraft (during takeoff and landing) rotating radar antennae, etc., must be able to operate in a reasonably strong surface wind, but it would be unreasonable to expect operations during extremely infrequent winds of say, hurricane force, even though the equipment should be able to withstand fairly rare extremes. Wind currents are often very localized, especially in rough terrain; hence, it is difficult to obtain speeds of various risks for the entire earth in order to select the windiest locations over which military operations are considered possible. Maps of the 1-, 2 1/2-, 5-, 10- and 20-percent probable 1-min steady wind speeds, based upon observations at major weather stations, are available for North America

34. Joint Typhoon Warning Center (JTWC) (1962) Annual Typhoon Report 1961, FWC/JTWC, Guam.

for every third month (GRD[35]). Because of strong dependency of windspeed on height above the ground at which it is measured, data for these maps were reduced to 10 ft, the level in MIL-STD-210A considered applicable to equipment.

Maps in this publication for the windiest month, January, for 1, 5, and 10 percent risk are presented as Figures 10, 11 and 12. The Great Plains, Aleutians, and coastal Canada's maritime provinces are noted for strong winds. This is quite apparent on the maps. If these were the windiest locations in the world of military interest, and a 1 percent risk were acceptable for inoperability, an extreme of 35 mph (or slightly higher) would be selected for the 10-ft level. A 10 percent risk would drop this to 25 mph. For areas with lesser winds, say, New England and Canadian Pacific coasts, a 25-mph speed is a 1 percent risk.

Stronger winds than those discussed for North America occur along the northern coast of Scotland and nearby islands. A survey of wind statistics over England (Shellard[3]) reveals that Stornoway, Scotland (58° 13'N, 6° 20'W, altitude 11 ft,

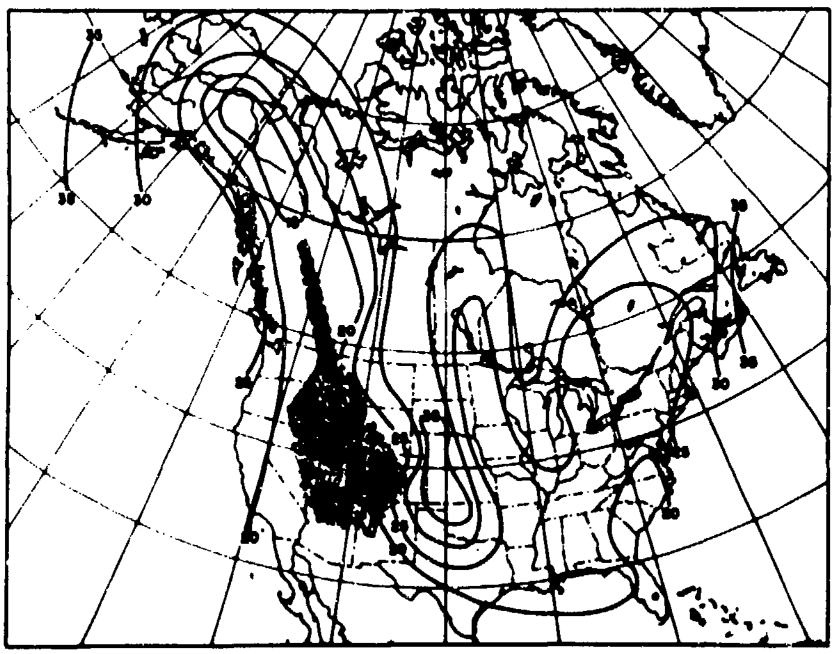

Figure 10. 1 percent Calculated Risk Steady Windspeeds (mph) at a Height of 10 ft, January (GRD, 1960)

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35. GRD (1960) Wind, Chapter 5, Handbook of Geophysics, AFRD, USAF, MacMillan Co., New York.

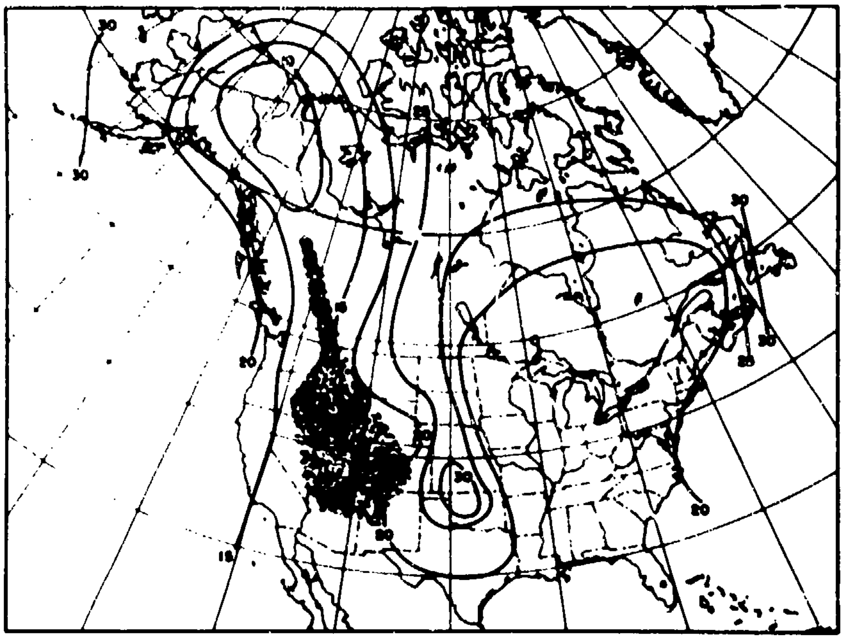

Figure 11. 5 percent Calculated Risk Steady Windspeeds (mph) at a Height of 10 ft, January (GRD 1960)

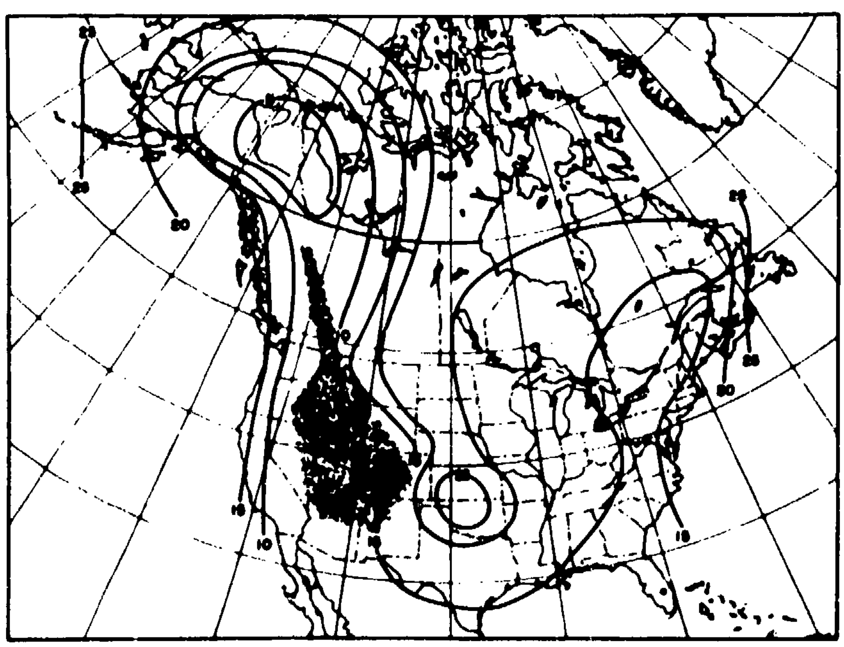

Figure 12. 10 percent Calculated Risk Steady Windspeeds (mph) at a Height of 10 ft, January (GRD, 1960)

anemometer height 36 ft) is typical of the general area with strongest winds, and December is the windiest month. Frequency distributions are available for 10-min averaged observations which are tabulated hourly. Another nearby station of interest is Lerwick, Scotland (60° 08'N, 01° 11'W, altitude 269 ft, anemometer height 37 ft).

The published 10-year, percent frequency distributions of hourly observations for the windiest month, December (other winter months are only slightly less windy), for these two locations, averaged over 10 min and corrected to a common height of 10 m (33 ft), are:

Speed (knots)	<4	4-6	7-10	11-16	17-21	22-27	28-33	34-40	>40
Stornoway (percent)	6.6	5.0	10.9	22.4	18.1	17.2	11.1	6.4	2.3
Lerwick (percent)	7.9	6.2	12.8	18.1	19.7	15.9	13.4	5.1	0.9

Converted to cumulative percent frequency exceeding the lower limit of each class these become:

Speed (knots)	0	4	7	11	17	22	28	34	40
Stornoway	100	93.4	88.4	77.5	55.1	37.0	19.8	8.7	2.3
Lerwick	100	92.1	85.9	73.1	55.0	35.3	19.4	6.0	0.9

These frequency distributions show that Stornoway is slightly windier than Lerwick.

To compare the winds at these Scotland locations to the values shown in Figures 10, 11 and 12, the 1-, 5- and 10-percent high windspeeds were first determined by plotting the distributions given above on probability paper. These 10-min averaged values must now be converted into 1-min speeds.

It was shown in Section 3 that gusts of several seconds can be represented by a multiple of the steady wind, the gust factor, which decreases as the steady wind increases. The ratio of the maximum 1-min speed to the speed averaged over 10 min can also be considered a gust factor in relation to speeds averaged over longer time periods. Durst[8] found that such long-time averaged gust factors were not especially sensitive to the steady speed in his sample which included speeds up to 42 mph. He determined that a value of 1.17 can be used to convert the 10-min values to 1-min speeds. His factors for shorter time intervals were comparable to those given in Table 7 in the speed intervals of 30-49 knots. This 10-min factor was used to convert the Stornoway and Lerwick data to 1-min speeds resulting in the following values:

		1-min Speed (knots) at 33 ft		
Probability (percent)		10	5	1
Stornoway	10 min	33	36	43
	1 min	39	42	50
Lerwick	10 min	30	34	40
	1 min	35	40	47

When reduced to a height of 10 ft by use of the power-law relation given in Section 4, and converted to mph to make them comparable to the values at the centers of wind maximum in Figures 10, 11 and 12, the following comparison can be made:

	1-min Speed (mph) at 10 ft		
Probability (percent)	10	5	1
Stornoway	38	40	48
Figures 10, 11 and 12	25+	30	35+

Evidently, low probability winds over the Scottish coasts are about 12 mph (10 knots) higher than the windiest North American area, and the speed of 43 knots at 10 ft seems appropriate to the 1 percent risk windiest month value for which military equipment should be designed. Values of 36 knots and 33 knots at 10 ft, associated with 5 percent and 10 percent risks, respectively, can be considered when the 1 percent goal is shown to be impractical (too costly or too cumbersome). It should be noted that special consideration has not been given to the "roaring forties" in the Southern Hemisphere which may have extremes exceeding those presented above. This area was notorious for windiness during the days of commercial sailing. Since there is little land area in this belt of strong winds, the area should not be important for "land" operations; however, it certainly merits special consideration when investigating extremes for the "Naval Surface" portion of MIL-STD-210B.

The design criteria for winds for military operations is the steady wind rather than short period gustiness, but the system designer must be aware of the gustiness which occurs concomitantly with the steady wind. To determine the most probable gust expected to accompany the 1 percent (5- or 10-percent) steady speeds of 43 knots (36 or 33 knots), the procedures outlined in Section 3 must be employed. It should be emphasized that it is not the gust that occurs 1 percent of the time, but rather, it is the median gust that will be present in conjunction with the 1-min steady speed which occurs 1 percent of the time.

It was shown in Section 3 that the structural response to wind gusts depends on the downwind dimension of the object. For example, if one were designing a

25- by 40-ft shelter, the most dynamically effective gust which could be expected to accompany the steady wind would have a gust length of 200 ft (8 times the shortest dimension, 25 ft). For the 1 percent speed, 43 knots (73 fps), the gust duration would be about 3 sec. From Figure 5, the expected gust factor for a 3-sec gust on a 43-knot 1-min steady speed is 1.23 resulting in a gust of about 53 knots. These values are applicable at a height of 10 ft. If the effective height of the shelter were determined to be 20 ft, these speeds should be converted, using Table 15 to a steady speed of 47 knots (1.09 x 43 knots), with a gust of 56 knots (1.057 x 53 knots).

For easier use by systems designers, gust speeds have been provided in Table 17 which are "scaled" to several sizes of equipment such that gust duration is sufficient for the gust to build up full dynamic force on the object. Since most equipment will not be installed with any special regard to the direction from which the extreme windspeeds will blow, the designer should design as if the shortest horizontal dimension of the object would be the downwind dimension.

Table 17. Operational Wind Extremes (based on Stornoway, Scotland): 1-, 5- and 10-percent probabilities of 1-min Steady Wind Speed and Associated Gusts. All speeds are in knots and apply to a height of 10 ft

Probability (Percent)	1-minute steady speeds (knots)	Most probable gust to accompany 1-minute steady speeds for various sized equipment (shortest downwind dimension).					
		2 ft (knots)	5 ft (knots)	10 ft (knots)	25 ft (knots)	50 ft (knots)	100 ft (knots)
1	43	62	59	56	53	50	48
5	36	52	49	47	44	42	40
10	33	48	45	43	40	38	36

5.1 Withstanding

In addition to being able to operate under wind conditions outlined above, equipment must also be able to withstand, without irreversible damage, that windspeed which can be expected to occur, with a 10 percent probability, during the projected field life termed "expected duration of exposure" (EDE) of the equipment at the area of the world subjected to highest windspeed extremes (10 percent probability of irreversible damage during the EDE was considered acceptable in the views of the JCS (SAES), as noted in the Background, Section 2).

For values applicable to equipment which must not be destroyed by the wind during several years exposure, annual extremes for many years are required for

application in extreme theory models. The cumulative frequency distribution of these extremes have been shown to fit the model made popular by Gumbel[36] and further explored by Gringorten[37]. Means and standard deviations of the annual extremes serve as a basis in this model of extremes. To determine 10 percent probability risks for field life exposure of up to 25 years, periods of record of 25 years or more are needed to reliably depict the double exponential distribution of extremes. Using this model, speeds determined for return periods of about 20, 50, 100 and 250 years are comparable to 10 percent risk within the expected field exposures of 2, 5, 10, and 25 years, respectively. (A more precise estimate of a 10 percent risk within a given period is possible, but resulting differences are negligible.) For example, a landing-aid antenna with an expected field life of 10 years should be designed for a speed that is attained only once in about 100 years, the return period. However, in using the model to obtain distributions for extremes, a standard deviation based on only a few years could be so unrepresentative of the true standard deviation that the 100-year return period speed could be either double or half that which would be obtained if the period of record represented the true distribution. Probably the best available data for this problem were carefully-edited annual extremes of 5-min speeds at 25 U.S. observatories for 37 concurrent years (Court[4]). Only records of stations with anemometers below 100 ft which were not changed by more than 10 ft during the period of record were treated with the extreme analysis theory. The 20-, 50-, 100-, and 250-year return period values for the ten stations with highest 250-year return periods are provided in Appendix C, Table C1. Coastal stations predominate because of the direct impact on them of tropical and very strong extra-tropical storms which develop their greatest strength over the oceans. The largest return period extremes are from Atlantic hurricane locations, the shorter return period extremes are from extra-tropical cyclones. Since Pacific typhoons are known to be stronger than Atlantic hurricanes, the search for the area in the world subjected to strongest annual extreme windspeeds was focused on data from the typhoon belts on the Pacific Islands and Asian coast.

Previous searches for the areas of extreme windspeeds, such as those for the Corps of Engineer's AF Manual No. 88-3[38], show that the worldwide highest windspeeds occur in the center of the typhoon tracks of the North Pacific. To insure

36. Gumbel, E. J. (1958) Statistics of Extremes, Columbia University Press, New York.

37. Gringorten, I. I. (1960) Extreme Value Statistics in Meteorology—A Method of Application, AFCRC-TN-60-442, AFSC No. 125, Bedford, Massachusetts.

38. Departments of the Army and the Air Force (1966) Load Assumptions for Buildings, Technical Manual No. 5-809-1, Air Force Manual No. 88-3, Chapter 1.

that no other locations had been overlooked, the Air Force's Environmental Technical Applications Center (ETAC) was asked to provide information which had been uncovered for earlier worldwide, high-wind searches, Appendix C, Table C2. In addition, ETAC was asked to provide listings of annual extremes of sustained and gust speeds for additional locations suspected of high extremes. The means, standard deviations and 10 percent risk speeds for 2, 5, 10 and 25 years for many of these stations are given in Appendix C, Table C3. The results confirmed the previous findings. The Volcano Islands (for example, Iwo Jima) and Ryukya Islands (for example, Okinawa) had the highest withstanding extremes, with a few stations in the Aleutian Islands running a close second.

One of the most severe typhoons to ever hit Iwo Jima occurred in 1955. The wind sensor and/or the recorder were not operational during the most intense part of the storm. The maximum 1-min steady speed was estimated to be 130 knots with the maximum gust estimated to be 175 knots at a height of 35 ft (corresponding to 111 knots with a maximum gust of 158 knots at a height of 10 ft). However, as stated in the beginning of this section, such estimated winds are not acceptable and, therefore, were not included in the data determining the means and standard deviations for Iwo Jima. On the other hand, to exclude data representing one of the most severe storms on record would be an unwarranted bias. To alleviate this situation, the second highest annual speeds (1-min steady of 107 knots and gust of 139 knots at 10 ft) were substituted for the 1955 estimated speeds. The resulting distribution is shown in Table C3 for Iwo Jima along with extreme wind distributions for other selected locations.

Unfortunately, the stations having the highest extremes have only about 20-year periods-of-record, falling short of the goal of at least a 25-year period-of-record. Therefore, these design extremes for winds may not be representative of the true distribution and should be considered again when five or more years of record become available.

Although Naha, Okinawa and Iwo Jima AB are about 900 miles apart, the 10 percent risk probabilities are very similar as can be seen from the data in Table C3. In the procedure for determining the return period extremes the high, mean annual gust speed at Naha is compensated for by the high standard deviation at Iwo Jima. Since each station had only 19 years of maximum annual gusts, consideration was given to combining the two samples if they were independent and representative of the same general wind extreme area. Despite their spatial separation, the correlation coefficient for their 14 common years, 0.44, was too high for such a treatment. Cumulative frequency distributions of the gusts for the two locations were plotted on extreme probability paper, Figure 13. Based on the means and standard deviations of the data, the straight lines, depicting the double exponential distribution of 2-sec gusts for the two stations are also shown.

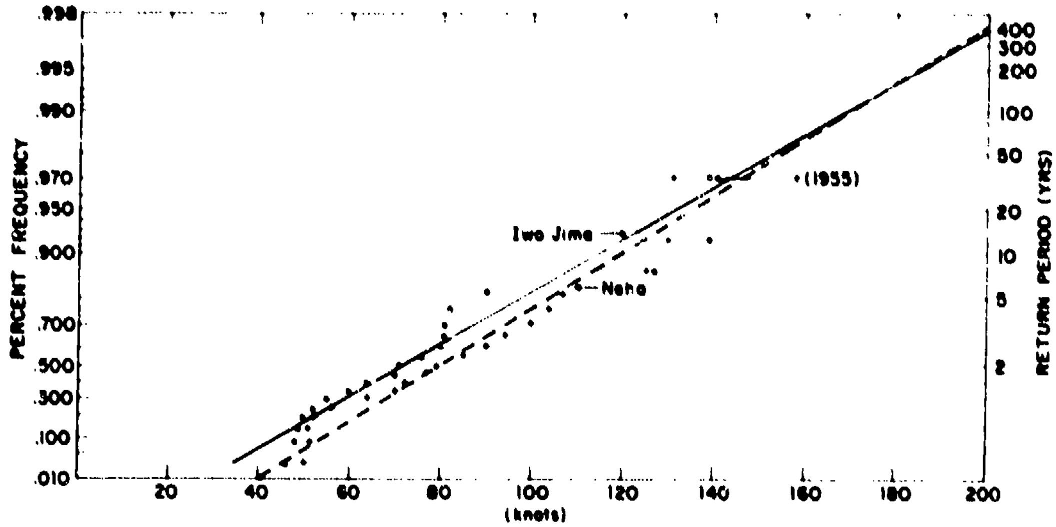

Figure 13. Probability Plots of Maximum Annual Gust Speeds at Iwo Jima and Naha

Analogous to normal probability plots, a double exponential distribution becomes a straight line when plotted on extreme probability paper. The line passes through the mean probability (0.5772 for this type of distribution) with a slope which is determined by the standard deviation of the distribution.

Since Iwo Jima and Naha had essentially identical return period gust extremes and there were no estimated windspeeds in the Naha record, Naha was chosen to be representative of the North Pacific typhoon belt and was used to establish the withstanding extremes for MIL-STD-210B. To scale the gust speeds to various sizes of equipment, similar to that in Table 16 for the Operational Extremes, the 1-min steady values for return periods of 20, 50, 100 and 250 years must be known. For many stations, including Naha and Iwo Jima, ETAC's data give the annual maximum 1-min steady speeds. Based on Naha's average annual 1-min maximum speed of 53.4 knots and standard deviation of 15.3 knots, the 10 percent risk probability for 2, 5, 10 and 25 years are 82, 93, 101 and 112 knots, respectively. Assuming that the annual maximum gust occurs during the annual maximum 1-min steady wind, the resulting gust factors are extremely high for such speeds. For example, based on the annual extreme data the median gust factor for Naha was about 1.65, whereas the data presented in Section 3 show that

for 1-min steady speeds of 80 knots or more, gust factors of less than 1.2 would be expected. The cause of this discrepancy was the manner in which the "maximum" steady values were recorded, as described below. The peak gust of the day is recorded in column 71 on WBAN 10 (the weather observation form in common usage for the NWS, Navy and Air Force). This value is determined by scanning the strip recorder chart. Since there is no column for the maximum steady speed, this value was retrieved from the archives by scanning the observation sheets for the highest steady speed listed on that form. When a "record" (hourly) or "special" observation is made, an eye-averaged, or 1-min speed is determined for a representative period of the observation and listed on the WBAN 10. As far as possible, this representative speed is not to be taken during periods of extremes, either high or low. Therefore, the highest 1-min steady speed associated with the peak gust (that is, the average for 30-sec either side of the peak speed), is not necessarily recorded on the WBAN 10 and may very well have been lost.

The nomogram in Figure 14 shows the expected relationship between the 1-min steady speeds and the 2-sec gusts. This curve was derived from the 2-sec gust

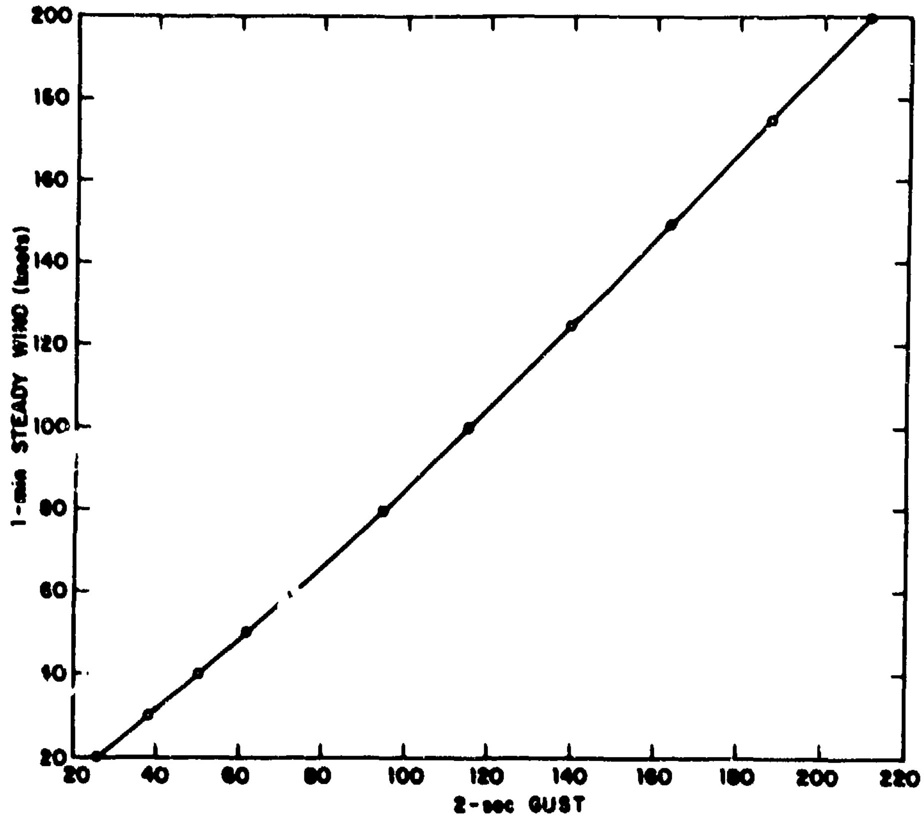

Figure 14. Expected 1-min Steady Speed to 2-sec Gust Relationship

factors given in Figure 5. Naha's 2-sec gust extremes (shown in Appendix C) were then used in Figure 14 to determine the 1-min steady winds (instead of the reverse procedure) so that the design gusts could be scaled to equipment sizes. The resulting 10 percent risk 1-min speeds for Naha, Okinawa for field exposure of 2, 5, 10 and 25 yrs are 119, 140, 156 and 176 knots, respectively. Following the same computational procedures as outlined in Section 5.3, the design speeds recommended for the worldwide withstanding extremes are given in Table 18.

Table 18. Withstanding Wind Extremes (Based on Naha, Okinawa): Scaled Gust Speeds and Associated 1-min Steady Speeds for 10 percent risk with 2-, 5-, 10- and 25-year Expected Duration of Exposure (EDE)

EDE (years)	1-min steady speed (knots)	Gust to be associated with the shortest downwind dimension of equipment					
		2 ft (knots)	5 ft (knots)	10 ft (knots)	25 ft (knots)	50 ft (knots)	100 ft (knots)
2	119	149	144	141	137	134	132
5	140	169	164	162	158	155	152
10	156	184	180	177	173	171	167
25	176	202	198	196	193	190	187

6. RECOMMENDATIONS

(1) Equipment designed for worldwide surface level deployment must be able to operate when the steady wind at 10 ft is 43 knots and gusts are 48 to 62 knots, depending upon horizontal dimension of equipment (Table 17). Steady winds and gusts for other heights may be obtained from Table 16. Values for greater risks are also provided in Table 17.

(2) Equipment designed for worldwide surface level deployment must also be able to "withstand", without irreversible damage, steady speeds of 119, 140, 156, and 176 knots at 10-ft height for estimated durations of exposure of 2, 5, 10, and 25 years, respectively. Gusts associated with these conditions could be as high as 202 knots, depending upon the horizontal extent of the equipment as indicated in Table 18. The values for other heights may be obtained by using factors in Table 16.

(3) Ice loading should not be added to the loads resulting from the wind extremes recommended above since extremes herein will occur at temperatures above freezing.

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Appendix A

Response Times of Operational Wind Instrumentation

Before one can evaluate the statistics of windspeed recorder data, it is necessary to determine the capability of cup and propeller anemometers to record short duration gusts. Approximately 85 percent of the data studied in Section 3 of this paper was recorded by a Friez Aerovane wind-velocity recording system which has a propeller as the speed sensor. This anemometer is used at a majority of Air Force installations. Mazzarella[1] studied the response characteristics and the overall performance of seven Aerovane speed sensors. He concluded that nearly all the transmitters were in good agreement after they had been used under severe conditions for long periods of time, so that degradation of equipment used in operations should not be an important influence. Most of the remaining 15 percent of the observations were recorded from 3-cup generator-type anemometers. Ramachandran[2] and Crouser[3] have studied the response of cup anemometers.

All generator-type anemometers are prone to errors caused by highly fluctuating wind conditions. Mazzarella[1] gives the error as less than 1 percent for winds fluctuating ± 14 percent around the mean. Ramachandran[2] states that "transient and

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fluctuating wind conditions show that a considerable amount of attenuation of the amplitudes of gusts, a large exaggeration of mean readings and a distortion in the gust shapes occur. The nonlinearity in the response characteristics of the anemometers is responsible for these results."

The response of cup and propeller anemometers is analogous to that of thermometers and other first order response instruments with the exception that instead of having a time constant as the basis of response, these instruments have a distance constant. The distance constant, used in conjunction with the "characteristic response function," (1-1/e), represents the length of wind which much pass the propeller (or cups) for the anemometer to indicate 62.8 percent of a step-change in speed. The distance constant for the Aerovane is about 15 ft (Gill[4] and Slade[5]) and about 26 ft for the typical 3-cup anemometer (Crouser[3] and Slade[5]). Experiments have shown that over the normal range of atmospheric speeds, the distance constant, L, is independent of windspeed, u. Consequently, since $L = u\tau$, the time constant, τ, is inversely proportional to the windspeed. This means the greater the step-increase in windspeed, the faster will be the response. This relationship is shown in Figure A1 which presents the percent of response versus elapsed time for anemometers with 15- and 26-ft distance constants. This figure shows that for step-increases of 20 knots or greater from a calm condition (neglecting starting friction), 99 percent of the increase will have been sensed within 2 sec for the Aerovane and within about 3.5 sec for the cup anemometer.

The response of these anemometers also depends on the speed of the steady wind upon which the gust is imposed. The higher the steady windspeed, the faster the response will be as shown in the following equation (Crouser[3]):

$$V_i = V_2 - (V_2 - V_1) \exp(-V_2 t / 0.6L) \tag{A1}$$

where

V_i = the instantaneous windspeed, knots, at elapsed time t,

V_1 = the original speed (assumed to be the mean speed), knots,

V_2 = the final speed (assumed to be the peak gust), knots,

L = distance constant (ft).

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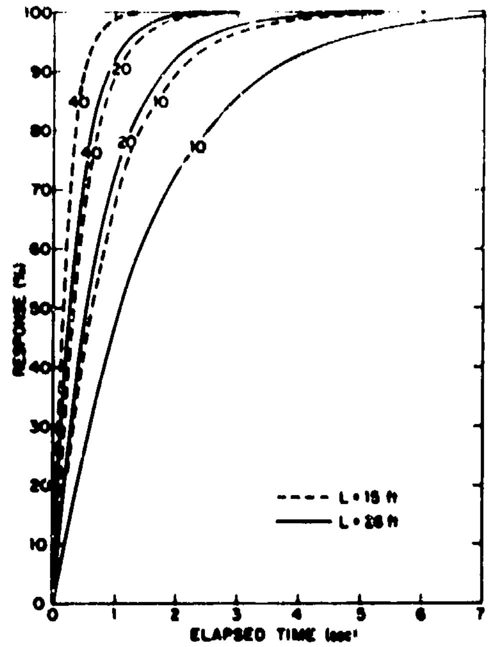

Figure A1. Ideal Response Characteristics for a Cup or Propellor Anemometer for 10-, 20- and 40-knot Step Increases From Calm (neglecting starting friction)

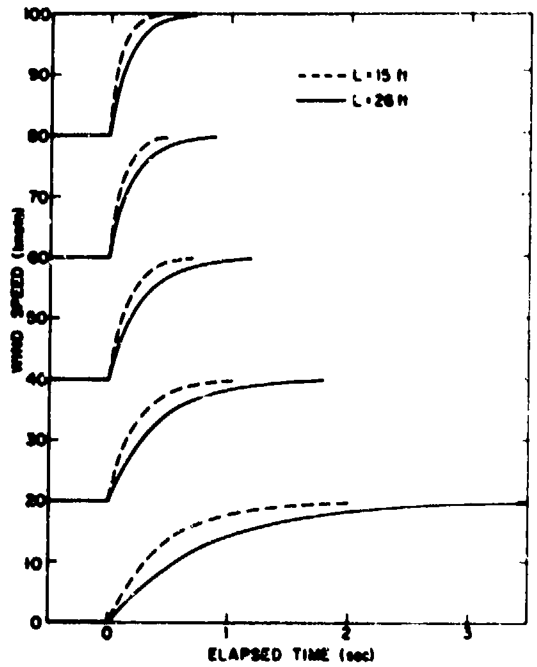

Figure A2. Ideal Response of a Cup or Propellor Anemometer to a 20-knot Step Increase From Mean Speeds of 0, 20, 40, 60 and 80 knots. The end of each response curve indicates the elapsed time required to achieve 99 percent of the gust (19.8 knots)

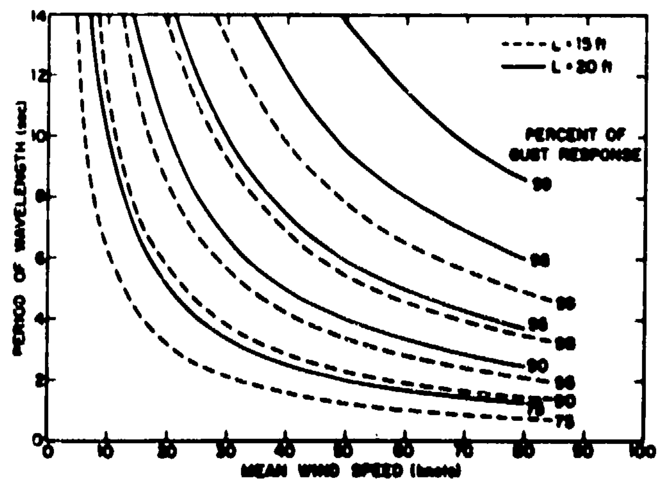

Figure A3. Anemometer Response to Sinusoidal Fluctuations

Figure A2 shows response times for a 20-knot step-increase at various mean speeds.

These two relationships, high mean windspeeds and large imposed gusts, combine favorably to provide faster anemometer response. Figure A2 shows that for mean speeds of 40 knots or better and a "step-increase" gust of 20 knots or better, 99 percent of the gust will be sensed in roughly 1 sec or less for both the cup (L = 26 ft) and propeller (L = 15 ft) anemometers.

Thus far, the discussion has been limited to a "step-increase" gust. This type of gust is a rough approximation for short intervals; that is, 1 sec or less. A more realistic approximation of wind fluctuations for somewhat longer intervals might be sinusoidal deviations around a mean windspeed. Such an analysis has been made by Gill,[4] who shows the relationship to be:

$$\frac{L}{\lambda} = \frac{\sqrt{\left(\frac{X}{X_i}\right)^2 - 1}}{2\pi} \tag{A2}$$

where

L = distance constant

λ = Gust wavelength = (mean speed, $\bar{u}$) x (wavelength period, t)

X = Actual amplitude of speed change

X_i = Indicated amplitude of speed change

For an anemometer with a given distance constant, Eq. (A2) can be applied to determine the wavelength period for various gust responses at selected mean windspeeds. The results of this procedure, shown in Figure A3, are hyperbolic curves of given percentage response. It can be seen from this graph that for a mean windspeed of about 50 knots with a 2-sec gust (4-sec period), anemometers with 26- and 15-ft distance constants will have responded to approximately 90 and 96 percent, respectively, of the actual amplitude of the gust.

It is not the intent of this paper to delve deeply into various aspects of anemometry, but it is necessary to be aware of the capability of anemometers to respond and to record atmospheric wind motions. The conclusions that can be drawn from this discussion is that for step-increase and sinusoidal-type gusts at high mean windspeeds (40- to [illegible] 1-min averages), the Aerovane will indicate between 95 and 99 percent of a 2-sec (half-wavelength) gust and the standard 3-cup anemometer will have sensed 90 to 99 percent of the gust.

Even if the wind sensor followed the windspeed perfectly, limitations imposed by the wind transmitter and recorder assemblies damp out the finest gusts, and

these are not indicated on the recorder chart. Because of this recorder limitation, H. H. Krauser of the National Weather Service and R. M. Peirce of AFCRL's Meteorology Laboratory—both authorities on anemometry instrumentation—have advised that peak gust speed on recorder charts of operational anemometers can be assumed to represent a 2-sec gust. This assumption was followed in the main body of this study.

Appendix B

The Dependence of Windspeed on Height Above the Ground in the Windy Acres Project of 1967

1. INTRODUCTION

In the power law, the windspeeds (V, V_o) at two levels above ground (H, H_o) are associated by

$$V/V_o = (H/H_o)^p \tag{B1}$$

where p is usually presumed constant. Thus, given a windspeed V_o at height H_o, the equation gives a corresponding windspeed V at height H.

In previous work, p has been assigned values varying from 0.05 to 0.8. Since investigators or authors have not always stated the temporal relationship between V and V_o, it usually has been supposed that V is the expected value of windspeed at height H that occurs simultaneously with windspeed V_o at height H_o.

This work explores the possibility of assigning values to p, recognizing its dependence upon (1) the magnitude of the speed at a specified height above the ground, and (2) averaging time of the wind measurement (for example, 1 sec, 10 sec, 1 min, etc.). Equation (B1) will not be used to estimate a profile to correspond to a given speed at the specified height; instead, it will be modified to provide the probability distribution of windspeed at height H when each percentile of the windspeed is assumed to be a function of height H only. A percentile of windspeed at one level does not necessarily occur simultaneously with the same percentile at another level.

The data on hand for this investigation consist of 39 hr of 1-sec windspeeds of the Windy Acres Project, taken in the summer of 1967 at 8 heights on a 32-m tower in southwest Kansas. The area is very flat and partly covered with wheat stubble 6 to 8 in tall. The 1-sec windspeeds did not exceed 15.3 m/sec.

2. METHOD OF ESTIMATING p

Equation (B2) can be written as

$$V_H = kH^p \tag{B2}$$

where V_H is the f-percentile windspeed at height H, and k is a constant for the given percentile (f).

Set $y = \log V_H$ and $x = \log H$. Then from Eq. (B2)

$$y = \log k + px \,. \tag{B3}$$

Using N heights along the tower where wind measurements are made, the estimations of p and k, by the method of least squares, are

$$\hat{p} = \frac{N\Sigma xy - \Sigma y \Sigma x}{N\Sigma x^2 - (\Sigma x)^2} \tag{B4}$$

$$\log k = \frac{\Sigma y \Sigma x^2 - \Sigma x \Sigma xy}{N\Sigma x^2 - (\Sigma x)^2} \tag{B5}$$

For the Windy Acres data, N = 8 where these eight heights are 1.5, 1, 2, 4, 8, 16, 24, 32 m. The windspeeds (V) are classified into sets according to the probability level of occurrence (f) and duration (m). The chosen probability levels (f) are

0.02, 0.10, 0.25, 0.50, 0.75, 0.90, 0.98, 0.998, 0.9998.

The chosen durations (m) in seconds are

1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 3600.

3. RESULTS

For each probability level (f) of the windspeeds and duration (m) a value of the exponent p was estimated from Eq. (B4) (Table B1). Figure B1 is drawn to show smoothed isopleths of the exponent p in the power law, as a function of duration (m)

Table B1. The Value of the Exponent p in the Power Law for Windspeed to Fit the 39 hr of 1-sec Winds in the Windy Acres Project of 1967. Heights of winds are from 1 2 to 32 m. (Bracketed figures are windspeed in mps at 8.0 m.)

Duration		Probability level of windspeed								
(m) sec	$\log_{10} m$	.02	.10	.25	.50	.75	.90	.98	.998	.9998
1	0	.71(2.4)	.22(3.3)	.20(4.0)	.17(5.0)	.14(6.6)	.12(8.8)	.11(11.3)	.09(13.1)	.08(14.2)
2	.30	.71(2.4)	.22(3.3)	.20(4.0)	.17(5.0)	.14(6.6)	.12(8.8)	.11(11.3)	.10(13.0)	.09(14.0)
4	.60	.71(2.4)	.22(3.3)	.20(4.0)	.17(5.0)	.14(6.6)	.12(8.8)	.11(11.3)	.10(12.9)	.09(13.9)
8	.90	.71(2.4)	.22(3.4)	.20(4.0)	.17(5.0)	.14(6.6)	.12(8.6)	.11(11.2)	.11(12.8)	.10(13.8)
16	1.20	.72(2.5)	.22(3.4)	.20(4.0)	.17(5.0)	.14(6.6)	.12(8.9)	.12(11.1)	.11(12.6)	.10(13.7)
32	1.51	.72(2.5)	.21(3.4)	.20(4.1)	.17(5.0)	.14(6.6)	.12(8.9)	.12(11.0)	.12(12.3)	.10(13.6)
64	1.81	.73(2.7)	.20(3.4)	.19(4.0)	.17(5.0)	.14(6.6)	.12(9.0)	.12(11.0)	.12(12.0)	.10(13.3)
128	2.11	.74(2.8)	.20(3.5)	.19(4.0)	.17(5.1)	.15(6.6)	.12(9.0)	.15(10.8)	.12(11.6)	.10(12.6)
256	2.41	.76(2.9)	.20(3.5)	.19(4.0)	.17(5.0)	.15(6.6)	.11(9.0)	.11(10.7)	.12(11.2)	.12(11.4)
512	2.71	.77(2.9)	.20(3.6)	.19(4.0)	.17(5.1)	.15(6.5)	.11(9.0)	.12(10.5)	.12(11.2)	.12(11.3)
1024	3.01	.78(3.0)	.20(3.6)	.19(4.0)	.17(5.1)	.15(6.5)	.11(9.0)	.12(10.5)	.12(11.0)	.12
2048	3.31	.65(2.9)	.19(3.6)	.19(4.0)	.17(5.1)	.15(6.5)	.11(9.2)	.12(10.6)	.12 -	.12 -
3600	3.56	.48(3.5)	.19(3.7)	.19(4.1)	.16(5.6)	.15(6.5)	.12(9.5)	.12(10.6)	. -	-

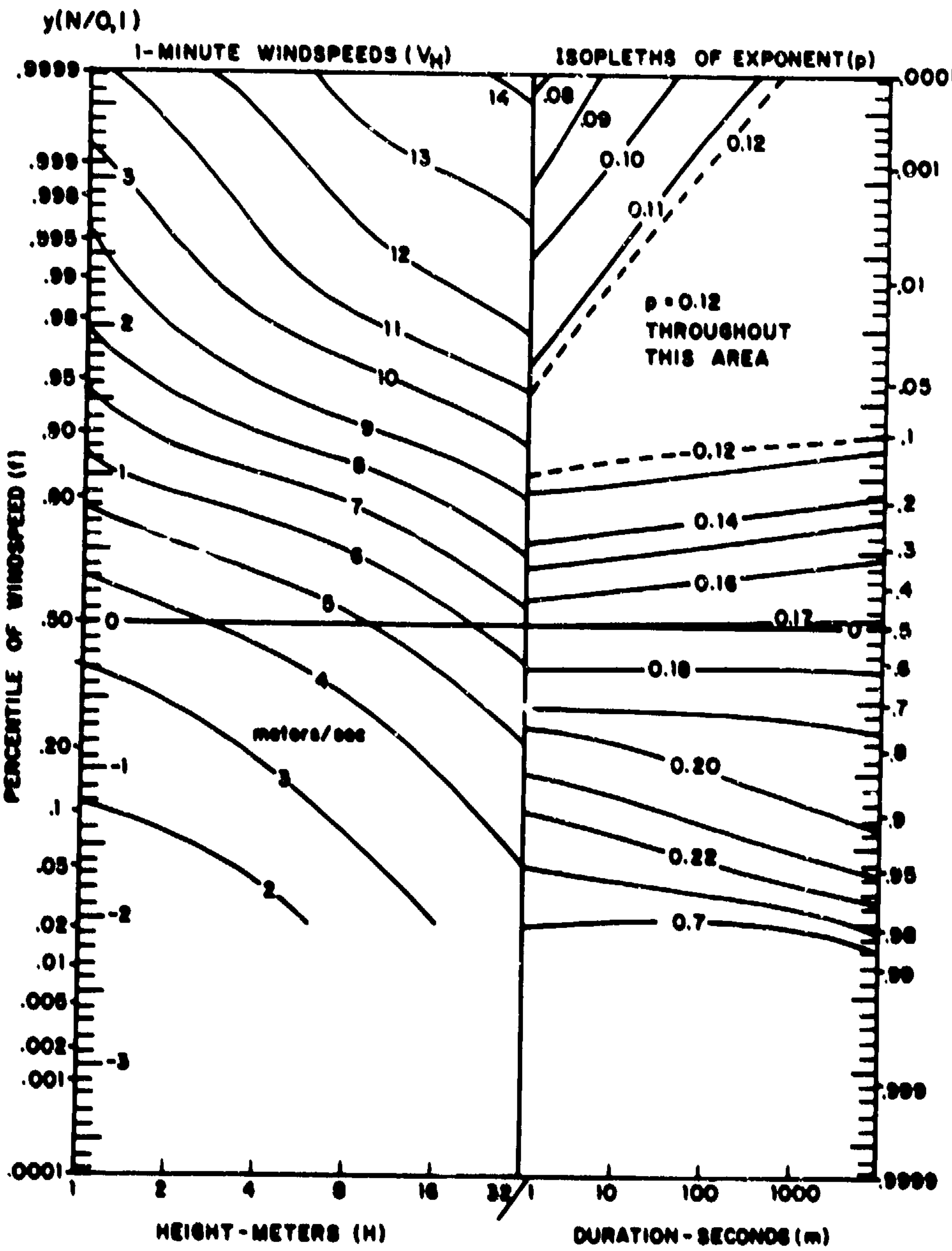

Figure B1. A Nomogram to Obtain Windspeeds of Duration 1 to 1000 Seconds at a Height of 1 to 32 Meters. Left-hand side shows percentiles of 1-min windspeed as a function of height above ground level. Right-hand side shows isopleths of p in the power law plotted as a function of duration and windspeed; read horizontally to the left side for given height and percentile

and the percentile of the windspeed. It also shows percentiles of 1-minute wind-speeds for heights from 1 to 32 meters.

4. CONCLUSIONS

These conclusions pertain to a study of windspeeds measured at 0.5 to 32 meters above the ground in which the fastest 1-second gust did not exceed 15.3 meters per second.

Table B1 and Figure B1 show a systematic variation of p with windspeed and duration. For the high speeds, the value of p is less than 0.13 and has been computed as low as 0.08. Up to the 90-percent windspeeds, the value of the exponent varies almost linearly with the windspeed from approximately 0.20 for the 15-percent winds to 0.13 for the 85-percent winds. But for the speeds equal to or greater than the 90-percent winds, the exponent p has an almost uniform value of 0.12, except for short durations of 1 min or less. (Previous work with the same data indicated that the Windy Acres winds became turbulent above the 95-percent windspeeds.) For gusts, the value of p varies jointly with their speed and duration, from 0.11 down to 0.08 for the unusually high 1- or 2-sec winds or gusts, suggesting a tendency toward a uniform intensity of turbulence with height as the speeds become greater.

5. REMARKS

This approach to the problem shows considerable promise, making it desirable to find more complete data than the 39 hr of Windy Acres data. Several questions remain unanswered. What is the effect of terrain and of thermal stratification? How should the vertical and horizontal dimension of the strong wind gusts be handled? While the value of 0.08 for p is the lowest computed in this exercise, it seems reasonable to expect a value close to zero if the turbulence is mixed thoroughly in both vertical and horizontal directions.

All told, the conclusions need to be considered tentative. Data are required in areas where the windspeeds are normally high to obtain information pertinent to strctural design.

Appendix C

Worldwide Wind Extremes

Table C1. Strongest 5-min Wind Expected in 20, 50, 100, and 250 years at 10 Locations in the United States With Anemometer Heights Below 100 ft (Court[6]).

Location	Return Period (years)			
	20	50	100	250
North Head, Wash.	84	90	95	100
Corpus Christi, Tex.	73	84	91	101
Tatoosh Is., Wash.	78	84	88	93
Block Is., R.I.	74	81	85	91
Key West, Fla.	66	75	81	90
Sheridan, Wyo.	60	68	74	81
Charleston, S.C.	60	67	72	78
Duluth, Minn.	62	66	69	73
Canton, N.Y.	57	62	66	71
Eastport, Me.	59	63	66	70

6. Court, A. (1953) Wind extremes as design factors, J. Franklin Inst. 256(No. 1):39-55.

Table C2. Extreme Wind Data Prepared by ETAC in 1964 (Anemometer Heights Are Not Standardized)

Location	Maximum 1-min			Peak Gust		
	Mean (knots)	S. D. (knots)	Period of Record (years)	Mean (knots)	S. D. (knots)	Period of Record (years)
Alaska						
Elemendorf AFB	35.5	5.6	14	58.8	8.7	12
Shemya Island	55.7	4.9	10	79.4	11.3	10
Davis AFB Adak NS				83.5	7.1	16
Cold Bay				71.1	9.8	21
Middleton Island				70.5	15.1	18
Greenland						
Narsarssuak AB				84.2	10.3	13
Sondrestrom AB				56.7	15.3	17
Simiutak AB				92.2	15.1	12
Thule AB	62.9	9.8	14			
Formosa						
Tainan	41.6	16.7	39			
Taipei	46.7	17.3	39			
Japan						
Itazuke AB	34.2	7.9	14	48.6	11.8	14
Misawa AB	37.3	5.6	11	53.3	10.7	11
Tokyo Intl. Arpt	40.7	9.6	15	56.3	10.8	15
Kimpo AB, Korea	33.3	6.3	8	40.1	7.6	8
Bangkok, Thailand				36.9	11.7	15
Peshawar, Pakistan				53.8	6.5	17
India						
Bombay	38.7	11.2	6			
Calcutta	44.7	5.8	6			
Gaya	41.2	5.4	6			
Madras	35.2	5.9	6			
New Delhi	40.5	3.0	6			
Poona	31.3	4.8	6			
Central AB, Iwo Jima	61.8	20.9	17	87.1	36.1	17
Kadena AB, Okinawa	64.7	20.0	14	91.4	25.5	14
Clark AB, P. I.	30.6	0.6	13	44.8	11.7	13
Hickam AB, Hawaii	35.1	6.6	17	44.8	9.5	11
Lajes Field, Azores	49.5	13.4	13	72.0	10.7	10
Albrook AB, C. Z.	21.3	3.3	18	31.1	5.1	14

Table C2. (Continued) Extreme Wind Data Prepared by ETAC in 1964 (Anemometer Heights Are Not Standardized)

Location	Maximum 1-min			Peak Gust		
	Mean (knots)	S. D. (knots)	Period of Record (years)	Mean (knots)	S. D. (knots)	Period of Record (years)
San Pablo (Sevilla), Spain	60.9	12.1	11			
Wheelus AB, Libya	39.1	9.3	14	51.1	8.2	14
Dhahran AB, Saudi Arabia				46.1	9.5	19
Stuttgart, Germany	32.1	3.8	15	51.8	7.9	13
Edinburgh, Scotland				65.2	5.6	21
Keflavik, Iceland	66.8	8.5	9	90.3	11.3	9
E. Harmon AB, Nfld.				64.9	9.9	15

Table C3. Selected Annual Extreme Wind Data Updated (1971) and Standardized at a Height of 10 ft

Location		Max 1-min Steady Wind Mean (kts)	S.D. (kts)	N (yrs)	Return Period* (yrs) 20 (kts)	50 (kts)	100 (kts)	250 (kts)	2-sec Extreme Gust Mean (kts)	S.D. (kts)	N (yrs)	Return Period* (yrs) 20 (kts)	50 (kts)	100 (kts)	250 (kts)
New Orleans, La (Callendar NAS)									43.7	14.6	11	71	82	89	100
Otis AFB, MA									49.4	9.0	12	66	73	78	84
Corpus Christi, Tex									50.8	10.2	24	70	77	83	90
Tainan, Taiwan		36.3	14.4	61	63	74	81	92							
Taipei, Taiwan		42.5	15.1	58	71	82	90	101							
Kindley AFB, Bermuda		47.7	14.5	15	75	85	93	104	58.9	11.6	12	81	89	95	104
San Juan, Puerto Rico		34.1	17.2	50	66	79	88	100							
Bally Kelly, North Ireland	Max Hourly	35.2	5.8	12	46	50	53	58	49.0	5.7	12	60	64	67	71
Stornoway, Scotland	Max Hourly	47.2	5.6	30	58	62	65	70	70.4	8.4	30	86	92	97	103
Thule, Greenland	Max 10-min	56.0	7.5	14	70	75	80	85	77.5	16.2	14	108	119	128	140
Thorshofn, Iceland		53.7	6.5	10	66	71	74	79							
Agana NAS, Mariana Is.		30.6	5.4	9	41	45	43	51	48.7	12.8	20	73	82	89	98
Anderson AFB, Mariana Is.		36.0	15.8	16	65	77	86	97	57.5	24.0	9	102	120	133	150
Saipan, Mariana Is.		24.4	6.8	15	37	42	46	51	43.7	14.1	15	70	80	88	96
Kadena AB, Okinawa		45.8	14.5	24	73	83	91	102	73.0	21.8	24	114	130	141	157
Naha AB, Okinawa		53.4	15.3	20	82	93	101	112	83.6	27.2	19	134	154	169	188
Iwo Jima AB, Volcano Is.	(with 1955)	51.4	24.5	22	97	115	128	146	77.7	31.7	19	137	160	177	200
	(Subst. for 1955)	51.2	24.0	22	96	113	126	144	76.7	29.2	19	131	152	168	189
Apia, Western Samoa									47.7	9.7	36	66	73	78	85
Eleuthera Island AAFB		33.3	14.8	17	61	72	80	90							
Adak NS, Alaska		40.1	4.8	8	49	53	55	59	76.3	9.4	28	94	101	106	113
Attu, Alaska		49.9	9.8	10	68	75	81	88	95.2	23.7	16	139	157	170	187
Shemya, Alaska		51.9	6.8	23	65	70	73	78	74.0	12.1	21	97	105	112	121
Gambell, Alaska		41.9	2.0	6	46	47	48	50	58.2	14.2	11	85	95	103	113
Nikolski, Alaska		49.9	9.1	15	67	73	78	85							
Northeast Cape AFS, Alaska		45.9	4.8	17	55	58	61	64	73.[illegible]	[illegible]1.5	7	95	104	110	118
Simiutak AB, Greenland		64.9	8.6	16	81	87	91	98	89.8	14.6	12	117	127	135	146
Wake Island, Pacific		35.6	21.5	18	76	91	103	118	45.1	24.6	24	91	109	122	140

* These return periods are applicable to exposures of 2, 5, 10 and 25 years with 10 percent risk